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Automatic gain control

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AUTOMATIC GAIN CONTROL

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AUTOMATIC GAIN CONTROL

by

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Chairman

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Academic Dean

PREFACE

The purpose of this thesis is to present the subject of automatic gain control as completely and concisely as practicable. It has been observed that most text and reference books dismiss the subject with a very few pages of description and circuit diagrams. Sturley (8) is an exception to this. Most papers written on the subject cover some particular phase quite completely, yet they confine themselves to that phase. It has been attempted here to cover the general subject from as many different aspects as has been considered necessary to give a complete picture.

Primarily, it is intended to point out that certain problems are encountered in designing a satisfactory AGC circuit, and that the solutions usually lie in the form of compromise, as is the case in so many electronic circuits.

It is hoped that this thesis will provide a groundwork of understanding of the subject of automatic gain control.

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LIST OF ILLUSTRATIONS

TABLE OF SYMBOLS AND ABBREVIATIONS

AGC	Automatic gain control.
Cf	AGC filter condenser.
Cgk	Grid-cathode interelectrode capacitance.
Cgp	Grid-plate interelectrode capacitance.
Ci	Input capacitance.
db	Decibels (used in voltage sense, i.e.: db = 20 log E_2/E_1).
Ed	Delay or threshold voltage.
Ein	R-f carrier input voltage.
Eout	R-f carrier output voltage.
F	Relationship of gain to Eout.
f_1	Relationship of AGC voltage to Eout.
f_2	Relationship of gain to AGC voltage.
g_m	Transconductance.
H	Flatness factor.
i-f	Intermediate-frequency.
Ib	D-c plate current.
k_1	Volts increase in rectifier d-c output per db increase in amplifier i-f output.
k_2	Gain reduction of controlled stages in db per volt of AGC bias.
M	Receiver gain.
m_1	Input modulation index.
m_2	Output modulation index.
r-f	Radio-frequency.
Rf	AGC filter resistor.

R_L	Load resistor.
rms	Root mean square.
V	AGC voltage.
Y	Transmission characteristic of feedback loop.
Ya	Transmission characteristic of r-f amplifier.
Ym	Transmission characteristic of r-f amplifier with AGC.
β	Feedback factor.
μ	Amplification of "μ" circuit in feedback system.

CHAPTER I

INTRODUCTION

1. Summary.

This thesis treats the general subject of automatic gain control. It covers in succession, what AGC is, where and why it is used, how it works, to what extent it works, types of AGC circuits, general characteristics of AGC action, speed of response, analysis as a feedback circuit, and the place of AGC in the present and in the future.

The various problems encountered in the design of a particular circuit are touched upon, and the major ones are covered at some length. The compromises necessary to obtain the most desirable results are explained. AGC is applied to most receiver circuits and these circuits vary widely; therefore, wherever examples are given, representative cases are taken which will best bring out that which is intended to be shown.

2. Definition of Automatic Gain Control.

Automatic Gain Control, abbreviated AGC, is defined as the process by which the amplification of a receiver is controlled by the output carrier voltage so that large variations of input carrier voltage cause comparatively small changes of the output carrier voltage. In practice, this is accomplished by utilizing in the receiver, tubes of such characteristic that the transconductance decreases with increase of grid bias. The AGC system develops a negative d-c voltage of a magnitude which is a function of the output carrier voltage. This d-c voltage is applied to the grids of the receiver tubes as bias, providing a system wherein the amplification is controlled by the output carrier voltage.

Ideal AGC would provide maximum receiver gain until the desired output was reached, after which further increase of input would not vary the output. By the very nature of the system, this ideal can be approached but never reached.

3. Historical.

One of the first attempts at automatic gain control was made in 1923. Triodes were shunted across the antenna circuit, and were biased from the detector output. This was primarily intended for the limiting of strong atmospheric noise.

Somewhat later, a mechanical form of AGC was developed which reduced the antenna coupling on strong signals. A milliammeter movement was connected in the detector circuit and actuated the moving plates of the antenna coupling capacitor, thereby decreasing coupling for stronger signals.

The introduction of the variable-mu r-f tube marked a most important step in the history of automatic gain control. With this tube it became possible to control the r-f gain by means of grid bias developed from the rectified carried output voltage.

One of the first published reports of an AGC system appeared in 1928. Wheeler (11) designed a tuned radio frequency receiver employing four UX201-A tubes in the r-f section, a detector, and a four-stage audio amplifier driving a loudspeaker. He fed the negative d-c component of the detected output carrier back to the grids of the r-f tubes, thus accomplishing his gain control in the same general manner as is done today. He called this circuit the "audiostat". He stated that a variation of input of 1000 to 1 could be reduced to a variation of 3 to 1 in the output.

In 1931 an AGC circuit was utilized in a radio beacon and receiving system for the blind landing of aircraft. This system was developed by Diamond and Dinsmore of the National Bureau of Standards and is one of the earliest applications of AGC to a complex and exacting system.

4. Applications of Automatic Gain Control.

Automatic gain control has application wherever large variation in carrier amplitude of input signal is likely to exist, but where it is desired to have this variation not appear in the output. Thus, in a radio receiver it reduces the effect of fading. It prevents an unduly large and sudden output when tuning from a weak to a strong signal. In high speed unmanned vehicles, it is desirable to compress the large variation in signal strength at the antenna which is due to variation in distance from the signal source, into a variation sufficiently small to be within the limits of usability of the devices into which the received intelligence is fed.

CHAPTER II

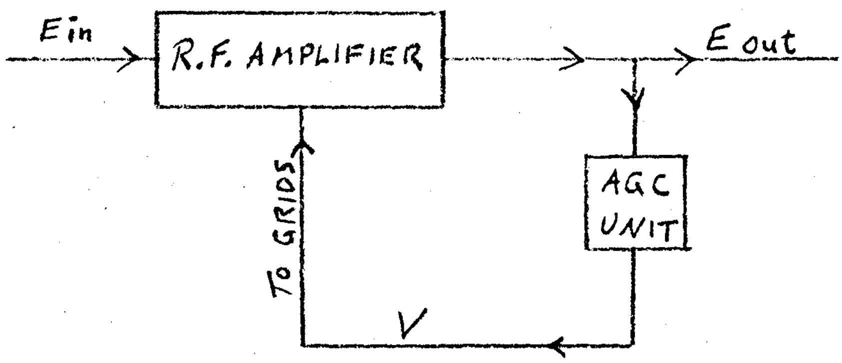
DESCRIPTION OF AUTOMATIC GAIN CONTROL

1. Theory of Operation.

An amplifier with automatic gain control is shown in block diagram form in figure 1. The amplifier gain can be varied by variation of grid bias. The r-f carrier input voltage Ein is amplified to a value Eout. Eout is applied to the AGC unit whose output is V, a negative d-c voltage which is a function of Eout. V is applied to the grids of the controlled stages and hence controls the gain of the amplifier. The AGC unit may be simply the detector circuit alone with an RC filter, or it may be an elaborate device consisting of a separate diode circuit, a means of providing delay, and a means of providing amplification. Depending upon the circuitry employed, the relationship of V to Eout will vary widely in form. Neglecting diode rectification efficiency, it may be equal to the peak value of Eout for simple AGC, or N X (Eout peak - Ed) where N is the amplification of the AGC system and Ed is the delay or threshold voltage. The gain of the amplifier is a function of V. This function, also, may vary widely. It is determined mainly by the g_m vs. grid bias characteristic of the controlled tubes and by the number of tubes to which the AGC bias voltage V is applied.

Let us define the receiver gain as M. We can then set up the following relationships:

$$V = f_1 \text{ (Eout)}$$



AMPLIFIER WITH AUTOMATIC GAIN CONTROL
(BLOCK DIAGRAM)

FIGURE 1.

$$M = f_2 (V)$$

$$M = F (Eout) = f_2 (f_1 (Eout))$$

$$Ein = Eout/M = Eout/F (Eout)$$

We know the V vs. Eout function f_1 from our proposed delay and amplification values of the AGC unit. We can obtain the M vs. V function f_2 from the composite g_m vs. grid bias characteristic made up from the type and number of controlled tubes. Combining these functions, we are able to make up a table or curve of the M vs. Eout function F. With this, using Eout as the independent variable, but plotting it as the ordinate, we can graph Eout vs. Ein where Ein = Eout/M. The characteristics of the various types of AGC circuits are plotted in this manner in Chapter IV.

2. Types of Automatic Gain Control.

Automatic gain control can be designed in several forms:

(1) Simple AGC. The negative d-c component of the detected carrier output is fed back to the grids of the controlled stages through a suitable filter network to provide the AGC bias. This type is simplest and least expensive, its minimum requirements being merely the addition of one resistor and one condenser to the circuit. The controlling action of simple AGC is correspondingly poor. However, it does provide a measure of control, and is satisfactory in receivers whose AGC requirements are less exacting. It is used in the less expensive receivers that include "automatic volume control" as one of the set's features.

(2) Delayed AGC. AGC bias is withheld from the

controlled stages until the output carrier has exceeded a "threshold" or "delay" value. This is accomplished by one of two general methods to be described later. The amount by which the output carrier exceeds this threshold value determines the AGC bias applied. Such an arrangement permits the utilization of maximum receiver gain until a satisfactory output is obtained, after which the gain-reducing action starts to take place. Delayed AGC requires an additional diode element.

(3) Amplified AGC. This type of AGC develops a bias which is a multiple of the voltage available from the detector output. It may be obtained in several ways, for example, by d-c amplification of the d-c component of the detected output voltage. Amplified AGC alone gives little improvement over simple AGC as regards regulation of output in db. This is shown graphically in Chapter IV and analytically in Chapter VI. The output for a given input is much less than for simple AGC, so that saturation of the i-f stages is less likely.

(4) Delayed and Amplified AGC. This combination method can most nearly approach ideal AGC. It combines the advantage of delayed AGC, namely maximum receiver gain until threshold is reached, with a feature of the amplified AGC. This feature is small output voltage variation with large variation of input signal. With increasing input, the output rises at maximum receiver gain until the threshold is reached. The amount by which the output exceeds this value is amplified

to provide the AGC bias. With large amplification, the output can be held very close to the threshold value. Thus a large dynamic range (the variation in input in db which can be accomodated for a given db variation in output) can be obtained by this method.

(5) Compensated AGC. The output from the next-to-last i-f stage is utilized as the source of AGC bias. It is amplified, detected, and delayed, and is used to bias previous stages in the conventional manner, and also to bias the last stage, whose output is detected as the audio intelligence. As far as the last stage is concerned, this is not AGC as previously defined. For this tube, its bias is determined by the input, not the output. Therefore, no error in output is required to provide a change of bias, and application of bias does not tend to reduce the source of bias. Thus, in this stage it is possible to obtain a decreasing output with increase of bias, and compensate for the rising AGC characteristic of the previous stages, obtaining substantially constant output at the detector. A conventional AGC system can provide bias to the first audio stage in a similar fashion, obtaining the same type of action.

3. Features and Requirements of an AGC System.

A satisfactory AGC system must possess certain features. These are: (1) Adequate dynamic range (delayed and amplified AGC if necessary to obtain this). (2) Satisfactory output for small signals (delayed AGC if required). (3) Control must be dependent upon output carrier voltage and independent of the modulation envelope (a filter problem). (4) The employment of AGC should not introduce distortion (a problem in tube selection, use of delay, and overloading of last i-f stage).

The above requirements for obtaining desired results are discussed in detail later. Certain other considerations in the application of AGC to a receiver are mentioned here:

(1) <u>Bias.</u> Some form of initial bias is necessary in order that the controlled tubes will be at a suitable quiescent point with no signal or with small signals before the AGC action commences. Except for one type of delayed AGC, cathode bias is most practical.

(2) <u>Input Capacitance.</u> The input capacitance of a tube varies with the gain: $Ci = Cgk + (M + 1)\ Cgp$, where M is voltage gain. Since the AGC voltage varies the gain of the tube, there will be a variation of input capacitance with variation of AGC bias. The use of the pentode tube has reduced the importance of this fact, but it must still be considered in certain applications. In superhetrodyne receivers working at the higher frequencies, it is usually desirable to use constant bias on the converter stage due to detuning effect on the local oscillator with variation of bias. In sharply tuned i-f amplifiers of high gain, there may be appreciable detuning effect due to insufficient tuning capacitance to "swamp" the input capacitance variation. At such high frequencies that tube and distributed capacitance provide the tuning capacitance, the effect becomes greater. In many

applications, a detuning can be tolerated on strong signals, in which case the tuned circuits are aligned on a weak signal, and the detuning due to strong signals is accepted.

(3) <u>Signal-to-Noise Ratio.</u> In the r-f stage, the factor $g_m/\sqrt{I_b}$ is important as a function of signal-to-noise ratio. This factor is maximum for normal values of bias, and decreases as the bias increases. For this reason it is desirable to apply only a fraction of the AGC bias to the r-f stage.

(4) <u>Tuning Indicator.</u> A receiver with an effective AGC system tends to maintain constant loudness of output when detuned a small amount to either side of the center of the response band. Hence, distortion may be present due to unequal transmission of the various side band components, yet loudness indicates proper tuning. A tuning indicator is therefore desirable. The "magic eye" or electron-ray tube, such as the 6U5, is customarily employed, and the AGC bias can be utilized to control the indication of the tube.

4. Factors upon which Automatic Gain Control Depends.

The response characteristics of an AGC system depend upon several factors. They are: (1) The g_m vs. grid bias characteristic of the tubes of the controlled stages. (2) The number of controlled stages and the degree to which each is controlled. (3) The magnitude of the output of the last stage before the detector. (4) The threshold voltage (if delayed AGC is used). (5) The amplification of the AGC circuit (if amplified AGC is used). (6) The initial bias. These factors will now be considered in detail.

(1) The slope of the g_m vs. grid bias characteristic is the key to any AGC system. The change in g_m (change in gain) per volt change in AGC bias determines the flatness of the AGC characteristic. The steepness of the curve can be thought of as AGC amplification. For example, if we had two tubes such that g_m for zero bias was the same, and if for all values, N/2 volts gave the same g_m for tube one as N volts bias gave for tube two, then tube one with no amplification would give the same AGC action as tube two with amplification of 2. Tubes of the remote cutoff or variable-mu type are designed for use in circuits employing AGC. The long tail of the g_m characteristic permits the application of large values of AGC bias (20 to 40 volts). This makes possible the obtaining of large output voltages with delayed and amplified AGC while staying within the conduction limits of the tube. If a small value of output is desired, i.e.: about one volt, the sharp cutoff tubes, such as 6AK5 and 6AS6, can be used with delayed and amplified AGC. The slope of their characteristics is steeper than those of the remote cutoff type tubes in the corresponding bias region, and an inherent amplification is thus obtained. Cross modulation will occur with excessive bias when using sharp cutoff tubes, however.

(2) The number of controlled stages also provides a measure of inherent amplification. Assume that we have a two-stage amplifier made of tubes whose g_m varies in the ratio of 5, 4, 3, 2 for AGC bias of 0, 1, 2, 3 volts re-

spectively. The amplifier gain will be proportional to $g_{m1} \times g_{m2}$. If we apply AGC to one stage only, the gain will be proportional to 25, 20, 15, 10. If we apply it to two stages, the gain will be proportional to 25, 16, 9, 4. Thus it is seen that when applied to two stages, the gain decreases as the square of the decrease for a single tube, for the same AGC voltages. If AGC is applied to N stages, the gain will decrease as the Nth power of the decrease in gain for a single tube. In terms of db gain, this means that a given AGC voltage applied to N stages reduces the db gain N times as much as if applied to a single stage.

Since in many applications, only a fraction of the AGC bias is applied to certain tubes, the gain reduction will not be as great in these tubes, and hence the above statements need modification in such cases.

(3) The magnitude of the output voltage of the last stage before the detector is the factor around which the AGC system must be designed. It is determined by the receiver gain and the expected range of values of the input signal. It is the source of the AGC bias and will therefore determine whether amplified AGC will be required to maintain the output within the acceptable limits. The minimum desired value of the output determines the delay or threshold voltage. In determining the action of AGC in a receiver, the output voltage is used to determine the bias, the bias to determine the gain, and the gain to determine the corresponding input, as previously explained. When such calculations

are made on a db basis, the reference level of the output must always correspond to a specific value of output voltage.

(4) The threshold voltage determines the input and output voltages at which the AGC action commences. In design work it is considered as the minimum usable value of output. It is an important factor in keeping the percentage variation in output small over the dynamic range of the receiver. This can also be expressed as keeping the db variation small, and is in contrast to the effect of amplified AGC, which, as is explained below, is to keep the voltage variation small.

(5) The amplification of the AGC circuit has the effect of reducing the gain more quickly with increase of output. Hence it requires a larger input to obtain a given output, and also a larger change in input for a given change in output than does simple AGC. Its improvement on the system is, then, primarily of reducing change of output voltage with change of input voltage, not of reducing ratio of output voltage. The ideal case is most closely approximated when delayed and amplified AGC is used, as was previously stated. Here the output variation is superimposed on a fixed value, the threshold voltage, and the amplification keeps the voltage variation small.

(6) The initial bias must be large enough to operate the tubes at a suitable quiescent point. On the other hand, bias should be low enough to utilize high receiver gain for small signals. Consideration should be given to the bias of the last i-f stage so that saturation will not occur before the output has exceeded the threshold value, permitting AGC bias

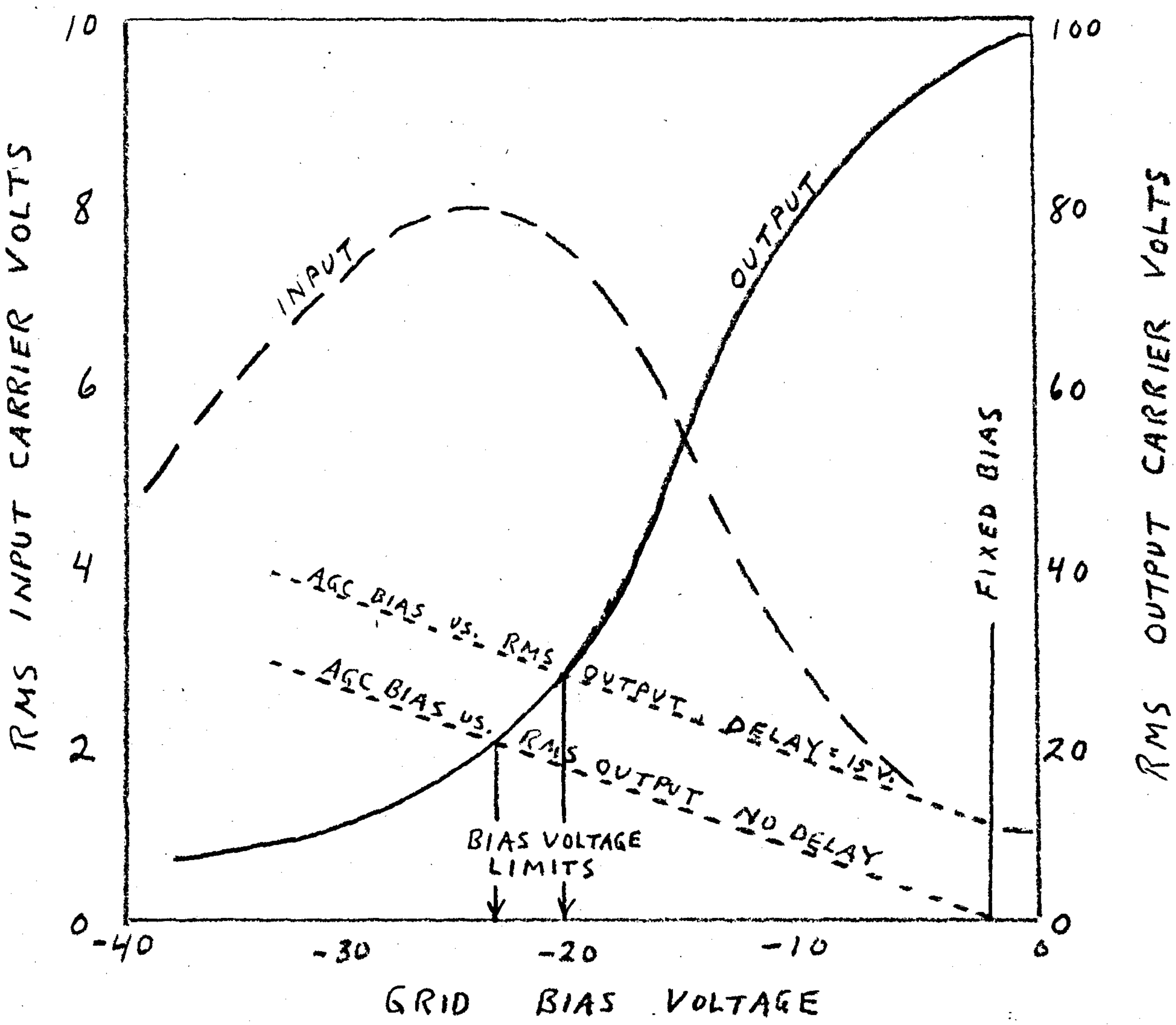
to prevent such saturation.

5. Limits of Automatic Gain Control Action.

The lower limit of input signal voltage whose output can be controlled is determined by the maximum gain of the receiver. It is the lowest input value which provides a measure of AGC bias. Of course, this can vary widely depending upon the delay used, if any. The upper limit is determined by overloading of the controlled tubes, normally the last, in spite of the applied AGC bias. The upper limit will be more fully explained below.

The signal handling capacity of a tube of the i-f amplifier is defined as the maximum input and corresponding output carrier voltage, modulated at a given frequency (normally 400 cycles per second), with a given percentage modulation (normally 30%), which can be obtained for a given percentage harmonic distortion of the modulation envelope (usually set at 5%). The maximum output under such conditions decreases with increase of bias. Hence curves of these input and output rms voltages vs. bias can be plotted. Such curves are shown in figure 2 by the dashed and solid lines.

For the AGC system we can determine the curve of AGC bias vs. rms output volts (the V vs. Eout function, f_1, of section 1). If we superimpose this curve on the graph of the signal handling capacity curve, the AGC bias curve will intersect the output curve at some point. Since any increase in input will give a larger output, which in turn will give a larger bias, the new point corresponding to output and bias will



LAST CONTROLLED STAGE

CURVES OF AGC BIAS VS. RMS OUTPUT VOLTS, SUPERIMPOSED ON SIGNAL HANDLING CAPACITY CURVE, SHOWING BIAS VOLTAGE LIMITS.

11320

FIGURE 2

lie to the upper left of the output curve, indicating distortion in excess of the amount for which the curve was calculated. Thus the intersection of the two curves gives the maximum output for the given percentage distortion of the modulation envelope. The input to the receiver, then, corresponding to this output, is the upper limit of input for which the output can be controlled. Plots of two representative AGC bias curves and their intersections are shown in figure 2.

To circumvent this condition and permit greater output without exceeding this distortion, less AGC bias may be applied to this stage than to the other stages. If a certain maximum AGC bias is determined to be necessary for the other stages, we can determine from the f_1 curve what rms output is necessary to obtain this bias. From the signal handling capacity curve, the value of bias where this rms output intersects the output curve is the maximum bias which can be applied to the last stage. Subtracting the initial bias from this value, we have the maximum AGC bias. The AGC bias for the last stage can be obtained from a voltage divider of proper ratio in the AGC circuit.

CHAPTER III

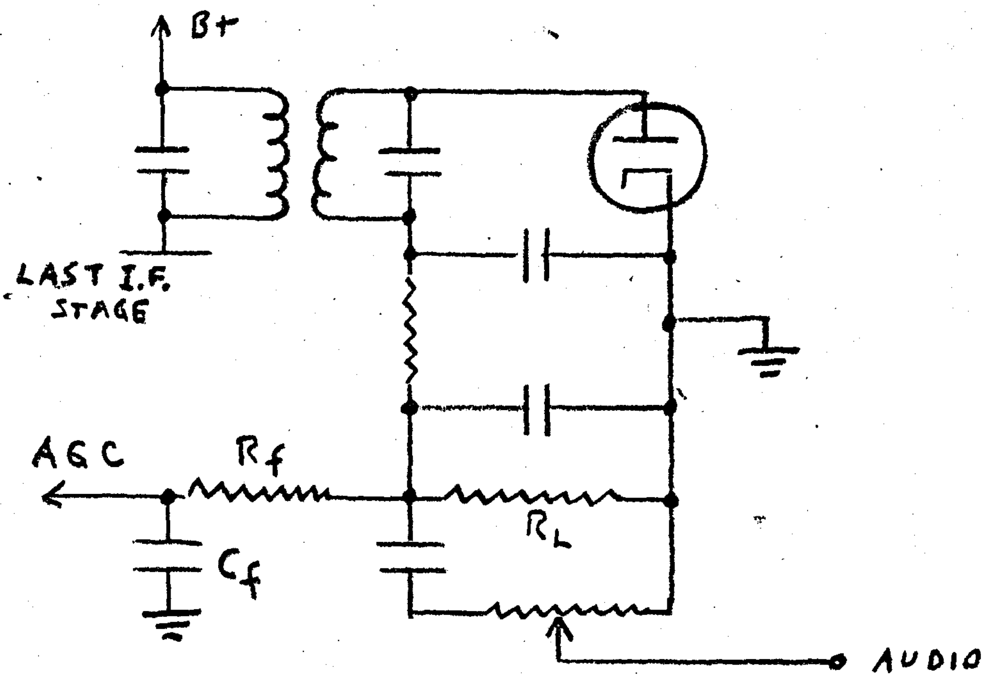
AUTOMATIC GAIN CONTROL CIRCUIT TYPES

1. Simple Automatic Gain Control.

Simple AGC can be obtained from the detector output by the expedient arrangement shown in figure 3. The negatively rectified detector output is taken, filtered of its audio component by the AGC filter, Rf and Cf, and applied to the controlled stages as bias. An example of simple AGC is shown in curve (2) of figure 12. These curves are explained more fully in Chapter IV, but the appropriate curves are indicated in this chapter as representative cases.

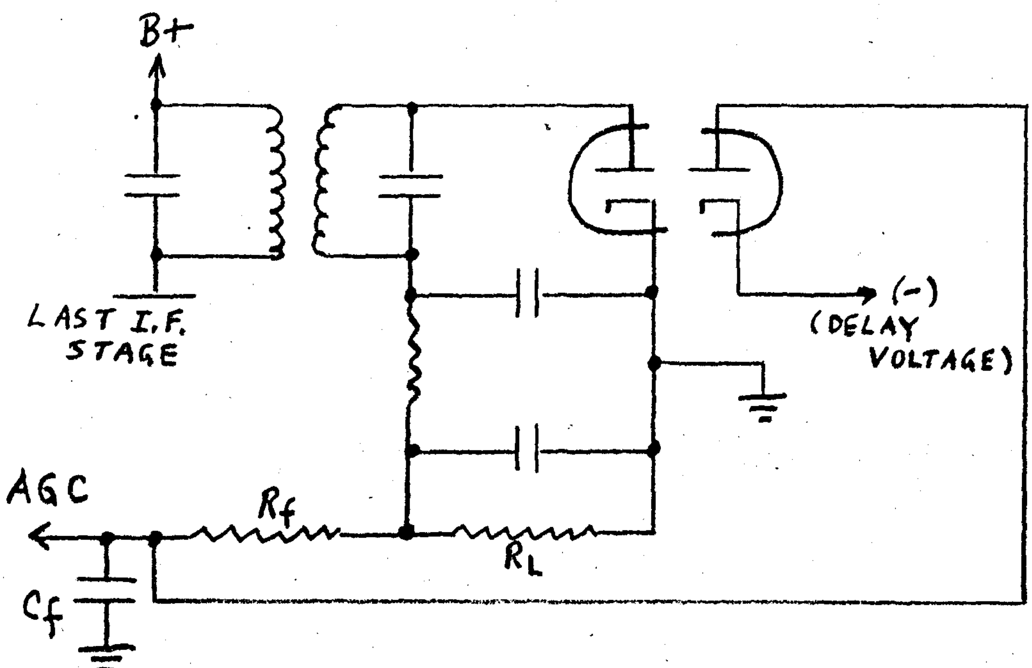
2. Delayed Automatic Gain Control.

Delayed AGC can be obtained as shown in figure 4, by employing a second diode whose plate is connected to the AGC bus and whose cathode is held at a negative voltage equal to the desired delay. As long as the rectified detector output is less than the delay voltage, the grids of the controlled stages will be held at the value of the delay voltage. When the detector output exceeds the delay, the diode plate is at lower potential than the cathode, and the tube ceases to conduct. The grids of the controlled tubes then take on the potential of the developed AGC. Providing the desired delay voltage does not exceed the nominal cathode bias of the controlled stages, the same maximum gain as for simple AGC can be maintained by reducing the cathode bias by the amount of the delay bias. In this case the initial grid-to-cathode



DETECTOR CIRCUIT WITH SIMPLE AGC

FIGURE 3

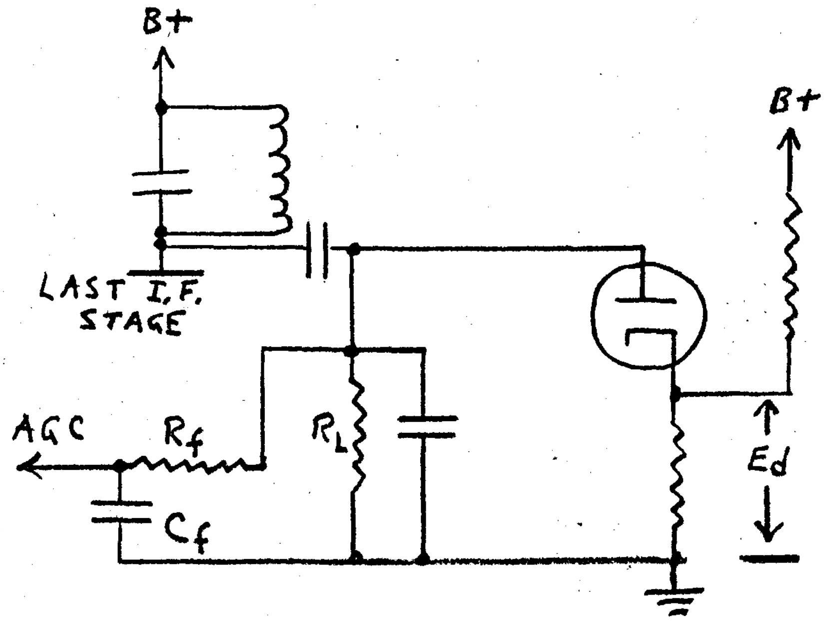


DELAYED AGC

FIGURE 4

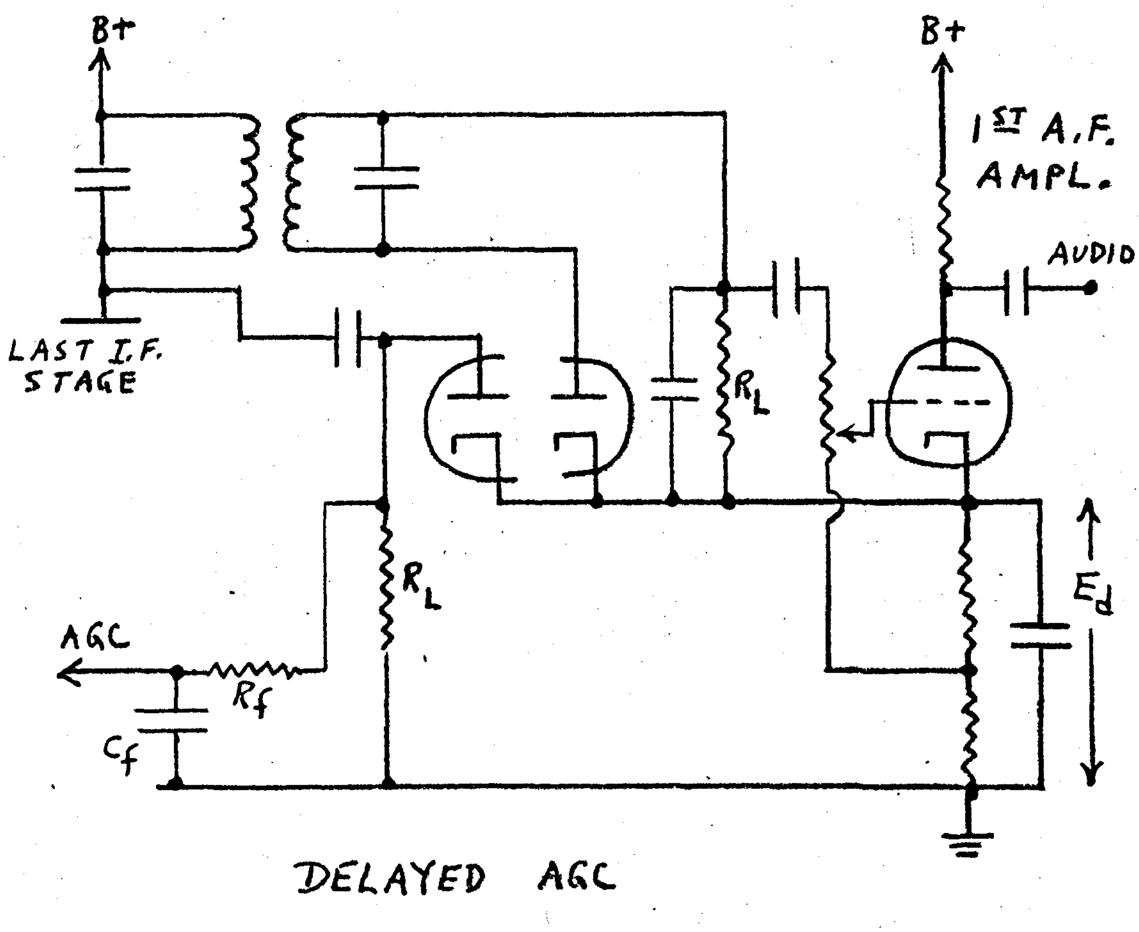
bias will be the same. This is shown graphically in curve (3) of figure 12. If no bias compensation is made, the output vs. input curve will be that for simple AGC after the diode has become non-conducting; prior to that point the curve will lie below the simple AGC curve, on a chord between the origin and the point on the simple AGC curve where the AGC bias equals the delay bias. This chord extended is the characteristic for no AGC with receiver gain being that for a fixed bias equal to cathode bias plus delay bias. Maximum gain in this case is less than that obtained if the cathode bias is reduced by the amount of the delay. Curve (1) of figure 12 indicates maximum gain in the latter case.

Delayed AGC can also be obtained by back-biasing a diode by Ed, the delay voltage, as shown in figure 5. The diode will not conduct until the output exceeds the delay voltage, and the AGC bias will be the amount by which the peak output exceeds the delay. This circuit also requires an additional diode, since if the same diode were used as both detector and AGC tube, there would be no detector output until the threshold voltage was reached. In actual practice the circuit could be designed as shown in figure 6. The detector voltage comes from the secondary of the interstage transformer. The detector load resistor is returned to the cathode so that no back-bias is applied to the detector circuit. The diode cathode is connected to the cathode of the first audio amplifier. To obtain grid bias for this tube, the grid resistor is tapped part way down the cathode resistor. The



DELAYED AGC (SIMPLIFIED SCHEMATIC)

FIGURE 5



DELAYED AGC

FIGURE 6

AGC diode is fed from the primary of the interstage transformer, capacitor-coupled. Since the AGC load resistor is grounded, and the diode cathode is above ground by the voltage drop across the cathode resistor of the audio tube, this cathode voltage serves as the delay bias for the AGC system. By taking the AGC voltage from the less-selective primary, the bias does not decrease so rapidly when the receiver is tuned off station, so the gain does not increase and give a large audio output when tuned off the center of the i-f pass band. This facilitates tuning and reduces the tendency to screechy reproduction due to unequal amplification of side bands when tuning on or off a station. A duo-diode-triode would normally be used in lieu of the two tubes shown in the figure. Separate tubes were shown to simplify the drawing.

A biased diode, such as is used in the latter-described method of obtaining delayed AGC, produces variable damping on the tuned circuit because during conduction it places additional load on the amplifier, reducing its gain. When the positive modulation envelope is below the delay bias level (diode not conducting), there is no distortion. When the positive modulation envelope is entirely above the bias level (diode conducts on every i-f cycle), the entire upper envelope is damped, but is identical in shape with the negative envelope, though reduced in size. This represents i-f harmonic distortion (which is rejected), but undistorted audio frequency output. However, if the delay bias line cuts the positive modulation envelope (diode conducts on the peaks of the modulation envelope but not on the troughs), then the modulation peaks are reduced in amplitude, and the troughs are not changed. This results in audio frequency harmonic distortion known as differential distortion. It should be noted that this distortion occurs only within a certain range of input values, the minimum input causing distortion being when the peak of modulation just exceeds the delay, and the maximum input being when the trough voltage does not quite equal the delay. It is thus a function of the percentage modulation. Differential distortion is a comparatively minor source of distortion, particularly with small delay bias.

It should be noted that the above-mentioned action creates another situation. Since conduction of the delay diode indicates development of an AGC voltage, then, with a modulated signal, the AGC bias will start when the modulation peak exceeds the delay voltage, not when the carrier exceeds this value. At the value of input which causes the entire modulation envelope to exceed the delay, however, and for all larger inputs, the AGC bias becomes independent of the modulation.

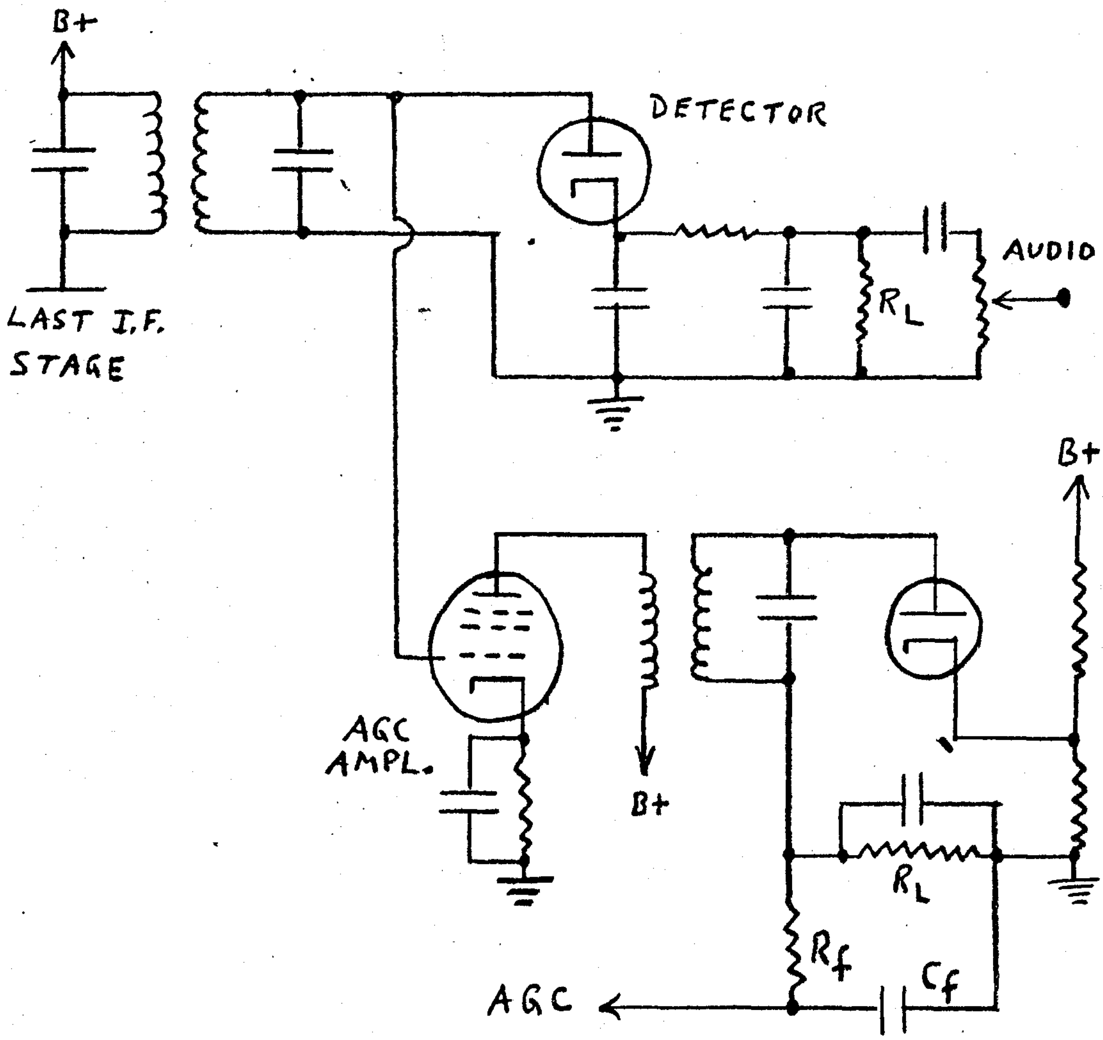
3. Amplified Delayed Automatic Gain Control.

Since most amplified AGC circuits will also utilize the advantage of delay, amplified AGC will not be discussed separately, but it should be clear how to obtain it if no delay were desired.

Amplified AGC can be obtained in practice by several methods, three of which will be described: (1) by further amplification at the i-f frequency beyond the stage where the output voltage is detected to audio frequency, and detection of this further amplified signal to provide an amplified bias, (2) by d-c amplification between the AGC bias voltage source and the controlled tubes, and (3) by plate detection at a negative potential.

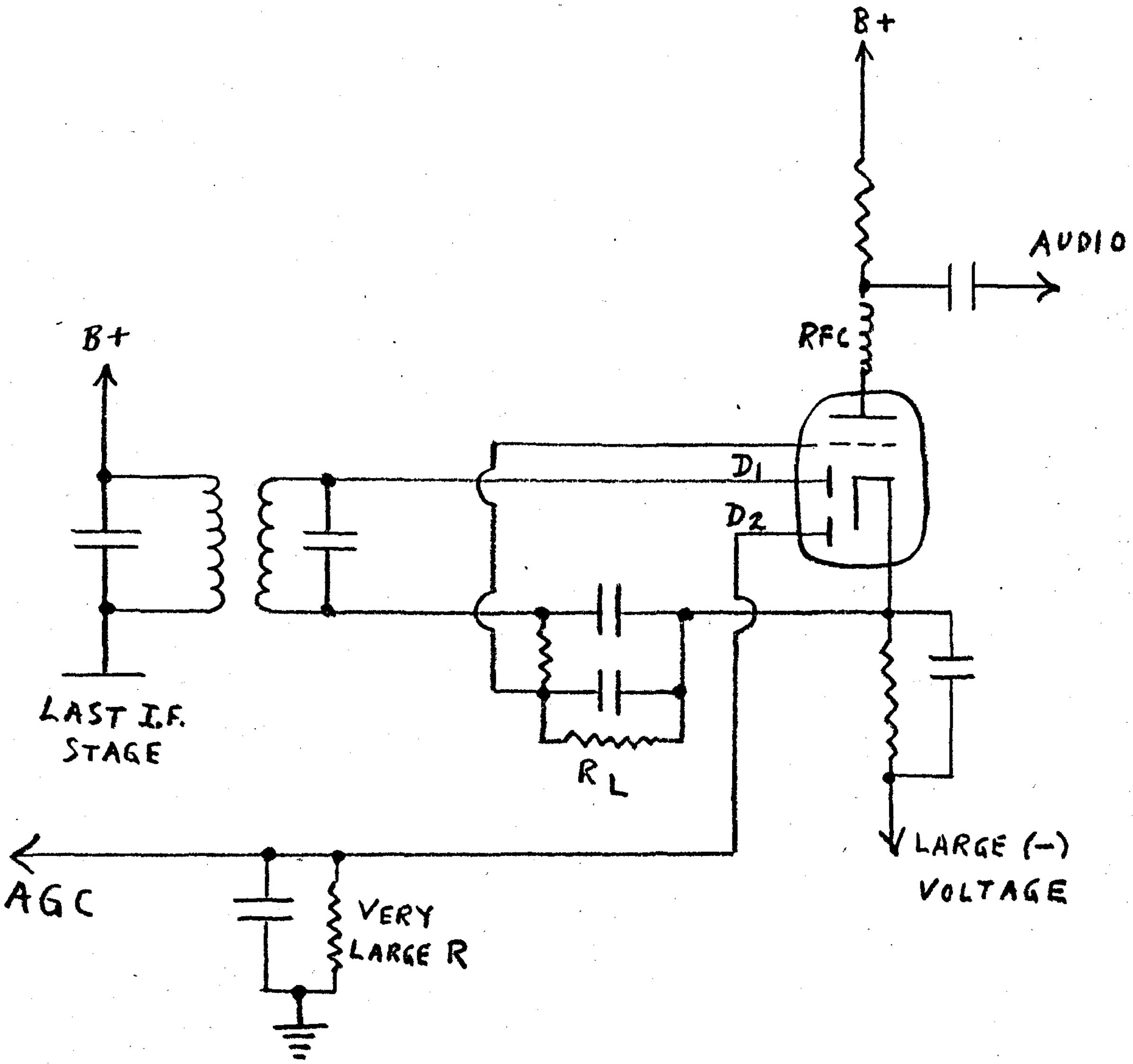
The method of further i-f amplification is shown in figure 7. The AGC amplifier provides a further stage of amplification. The AGC detector is simply a back-biased diode, the bias coming from the positive supply through a voltage divider, being of a value equal to the threshold voltage. Although this method requires the use of a separate i-f amplifier stage, it possesses many advantages: There is no loading on the main i-f amplifier tuned circuit as long as grid current is not drawn by the AGC amplifier. As long as it does not draw grid current, any form of distortion that may occur in its output is irrelevent. The characteristic of the AGC diode tuned circuit can be made non-selective to decrease the amount of bias reduction when slightly detuned as discussed in section 2. No negative voltage supply is required. This type of circuit, where the AGC voltage comes from a separate branch of the i-f system, lends itself to use in compensated AGC systems, to be discussed later.

The method of d-c amplification is shown in figure 8. Operation is as follows: The rectified output of the diode D_1 is applied between the grid and cathode of the amplifier



I.F. AMPLIFIED AGC

FIGURE 7



D.C. AMPLIFIED AGC

FIGURE 8

tube. This tube has its cathode returned through a large resistance to a negative voltage supply. The initial adjustment for no signal is such that the cathode is slightly positive with respect to ground by an amount determined by the desired threshold voltage. Rectified output produced by an incoming signal biases the grid negative by an amount proportional to the amplitude of the incoming signal. This reduces the plate current and causes the cathode voltage to decrease by an amount determined by the gain of the amplifier and the size of the cathode resistor. As long as the cathode is positive with respect to ground, the AGC bus remains at ground potential. When the cathode is negative with respect to ground, the diode D_2 conducts and the AGC bus assumes cathode potential. This method permits obtaining delayed amplified AGC with but a single tube which acts as detector, AGC diode, and first audio amplifier.

The method of plate detection is shown in figure 9. A source of negative voltage is required. A triode is connected as shown, the cathode being made positive with respect to the grid by the voltage divider action of R_k and R_1, R_k is variable and is set to bias the tube below cutoff by an amount equal to the desired threshold voltage. The i-f voltage is capacitor-coupled from the less selective primary and fed to the grid of the AGC tube. The plate resistor R_L, normally 0.1 megohm, is bypassed for i.f. by the condenser C_o. Normal plate detector action takes place in the tube. Positive i-f pulses in excess of the delay cause the tube to conduct.

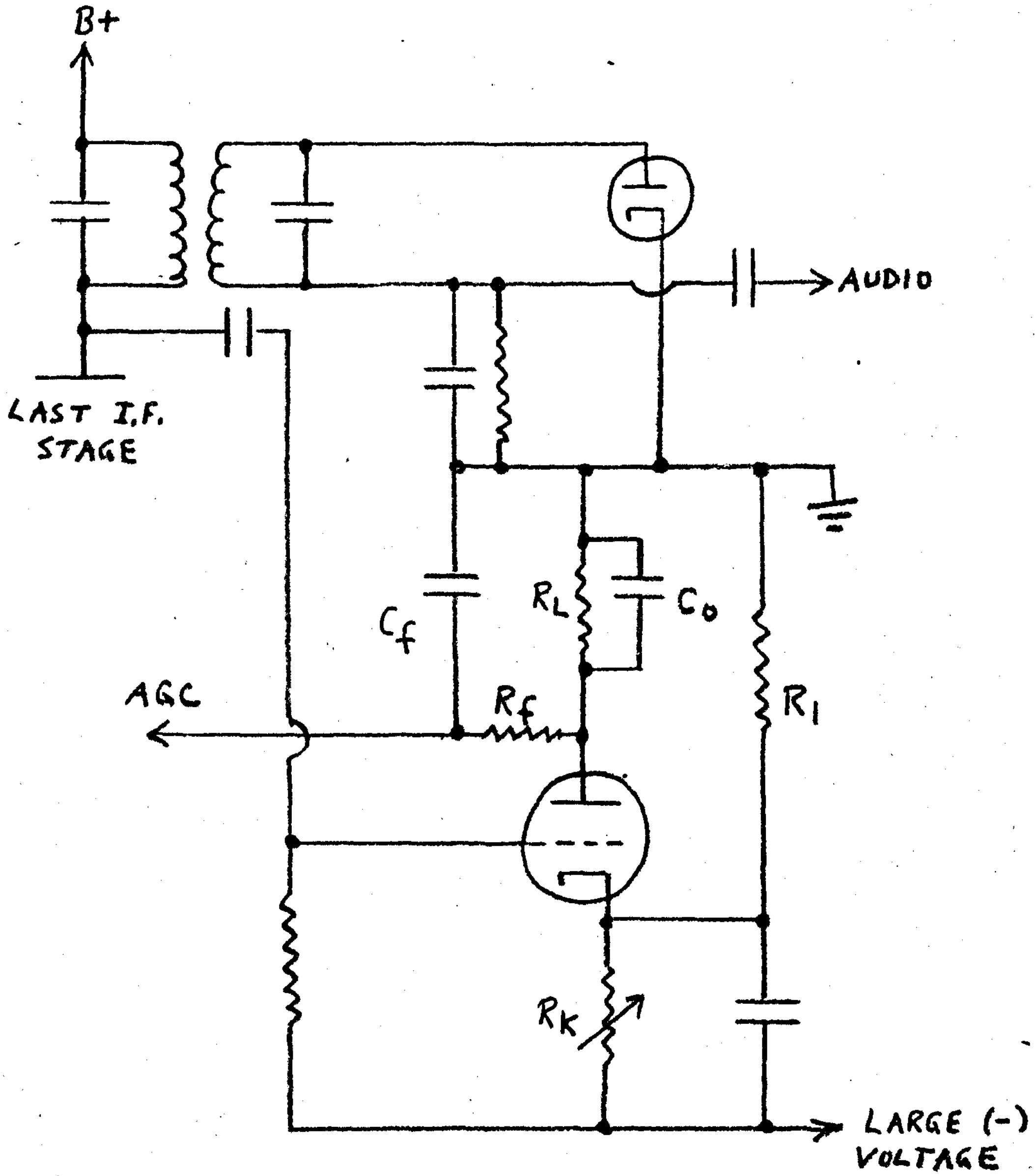


PLATE DETECTION AMPLIFIED AGC

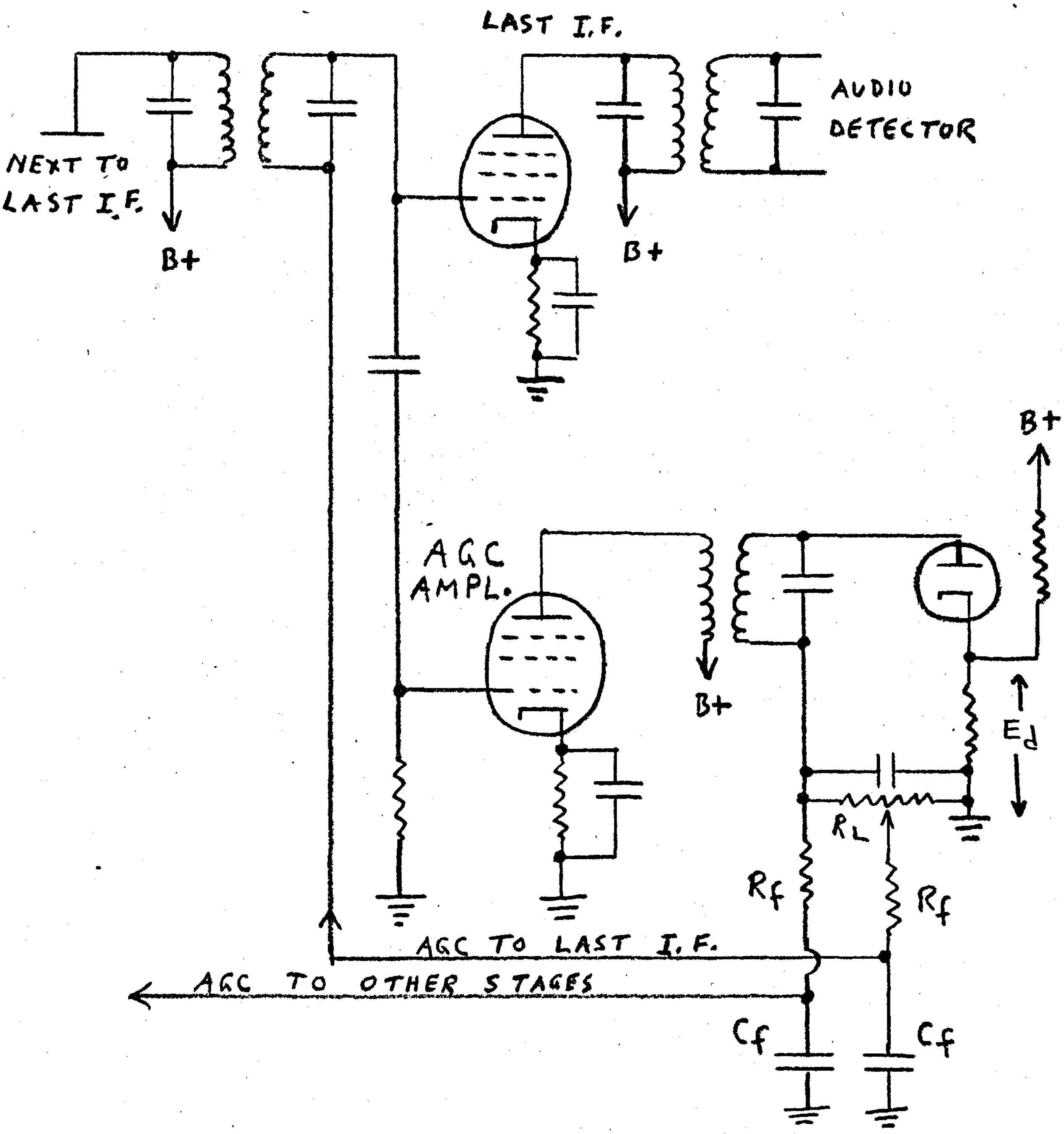
FIGURE 9

The larger the i-f output, the larger will be the pulses of the positive half cycles applied to the grid, and the lower will be the average value of plate voltage (i-f pulsation is bypassed in the plate circuit by C_o). The plate, then, will vary at an audio rate about an average plate potential, which becomes lower with increase of the average input pulse height. The AGC filter, Rf and Cf, removes the modulation, and we then have an amplified AGC bias determined by average carrier output above the threshold value. The parabolic characteristic of the plate detector tends to give an improved AGC characteristic, because the bias increases at a greater rate than does the carrier.

Curves (5), (6), and (8) of figure 12 are examples of amplified AGC.

4. Compensated Automatic Gain Control.

A typical compensated AGC circuit is shown in figure 10. The source of AGC bias comes from the input circuit to the last i-f amplifier. The circuit is very similar to that of the first-described amplified AGC circuit. However, a part of the AGC voltage is used to bias the last i-f amplifier, providing a decreasing characteristic with increase in input in this stage, as was described in section 2 of Chapter II. This gives a more nearly flat AGC characteristic for the entire amplifier.



COMPENSATED AGC

FIGURE 10

CHAPTER IV

AUTOMATIC GAIN CONTROL ACTION

1. General.

Ideally, an AGC circuit would provide increasing output with increasing input at maximum receiver gain until the desired output level is reached; further increase of input signal would cause no additional increase in output. This ideal operation cannot be achieved in an AGC system in which the control is obtained from the output of the controlled stages, since some error in output is necessary to provide the control as is the case in any closed feedback loop. However, by employing the various types of AGC, or combinations thereof, ideal operation can be approached to a greater or lesser degree depending upon the demands of the system to which applied and the additional circuitry which can be accepted.

2. Method of Obtaining Output versus Input Characteristic.

To show the various ways in which AGC can be applied, a two-stage amplifier employing 6AK5's will be used as an example. The g_m vs. grid bias characteristic for this tube with condition of plate voltage 180 volts, screen voltage 120 volts is shown in figure 11. Also shown is voltage gain for an effective load of 4000 ohms (gain $= g_m \times R_L$). We shall consider an initial bias of two volts on the tubes. For simplicity, we shall assume that rectified d.c. is equal to Eout (for condition of no delay). Arbitrarily, this presumes rectification efficiency of 100% if Ein and Eout are peak

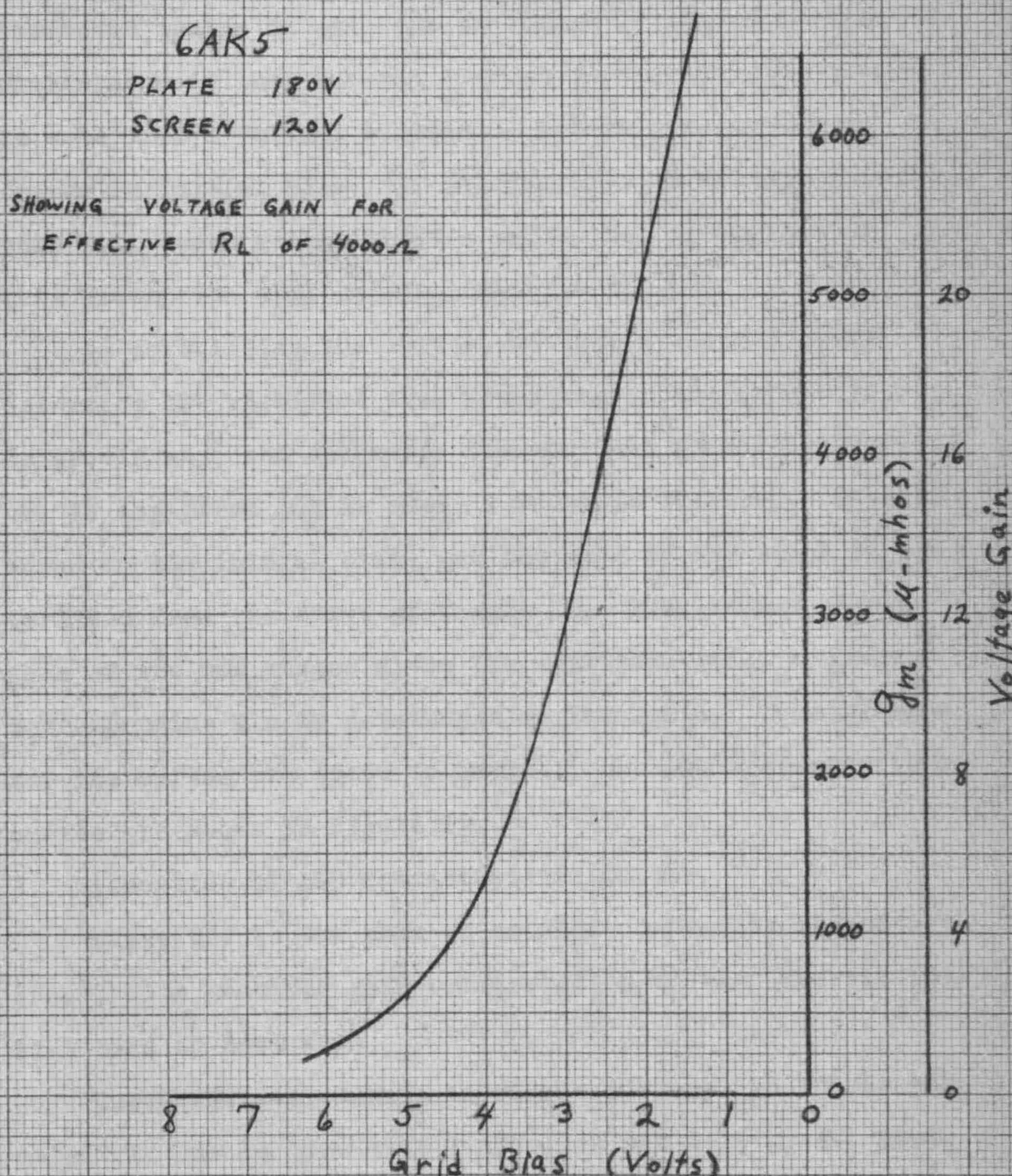

6AK5
PLATE 180V
SCREEN 120V
SHOWING VOLTAGE GAIN FOR
EFFECTIVE RL OF 4000Ω
6000
5000
4000
3000
2000
1000
0
20
16
12
8
4
0
gm (μ-mhos)
Voltage Gain
8 7 6 5 4 3 2 1 0
Grid Bias (Volts)

FIGURE 11

voltages, or 71% if they are rms values. Assume the desired Eout to be one volt. Assume unmodulated carrier. Further, assume no change in gain due to change in screen voltage with change in tube current (screen voltage may be assumed to come from a voltage divider). Let us also assume no change in initial bias. If initial bias is cathode bias, this will cause an appreciable error, but the effect of this assumption will be shown later.

In calculating the curves, we take a value of Eout, determine the rectified d.c. according to the amount of delay, if any, and determine the AGC bias (rectified d.c., or, if amplified AGC is used, a multiple thereof). This is added to the initial bias, and the gain of the stage is determined from the curve of figure 11. The product of the gain of the two stages gives the amplifier gain, and the corresponding Ein is determined as Eout/gain. Calculations for the curves are shown in Table I; the AGC characteristic curves are shown in figure 12.

3. Discussion of AGC Characteristic Curves.

Curve (1) is the case of no AGC. Output is linear with input, with receiver gain corresponding to the two-volt initial bias on each tube.

Curve (2) corresponds to simple AGC applied to one tube only. It can be seen that control is not very good. Also, weak signals are biased down before the output reaches the desired level. On the other hand, it is a decided improvement over (1), particularly as to the magnitude of input

CALCULATIONS OF OUTPUT VS INPUT CURVES WITH A.G.C.

CONDITIONS: TWO 6AK5'S IN CASCADE, EFFECTIVE $R_L = 4000\Omega$, INITIAL BIAS = −2 VOLTS.

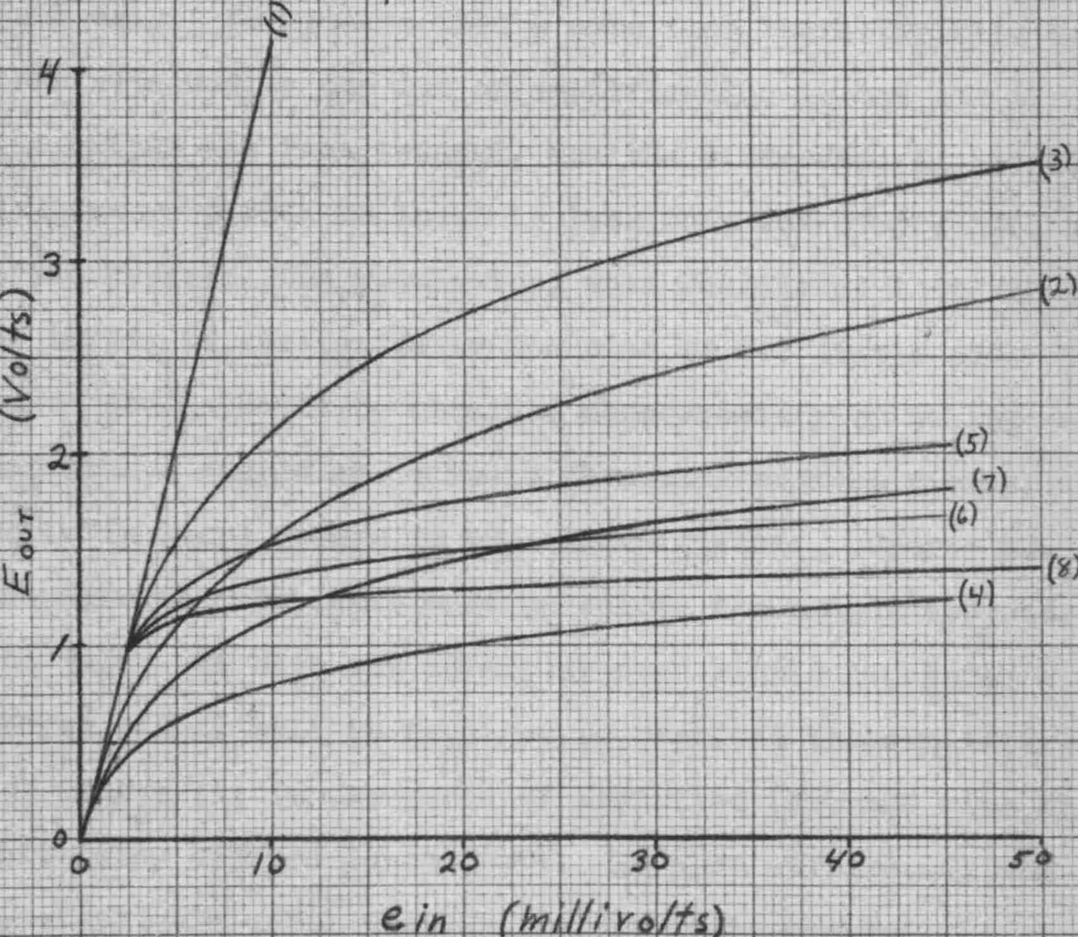
ASSUMPTIONS: RECTIFIED DC IS EQUAL TO EOUT, FOR NO DELAY. NEGLECT CHANGE IN CATHODE BIAS AND CHANGE IN GAIN DUE CHANGE IN SCREEN CURRENT.

E OUT	RECTIFIED D.C.	BIAS (−) AGC	BIAS (−) INITIAL	BIAS (−) TOTAL	VOLTAGE GAIN TUBE 1	VOLTAGE GAIN TUBE 2	VOLTAGE GAIN TOTAL	e in = EOUT/GAIN
NO AGC (CURVE 1)								
ALL VALUES	—	—	2	2	20.4	20.4	416	1/416 EOUT
SIMPLE AGC APPLIED TUBE 2 ONLY (CURVE 2)								
.5	.5	.5	2	2.5	20.4	16.0	326	.0015
1.0	1.0	1.0	"	3.0	"	11.8	241	.0041
1.4	1.4	1.4	"	3.4	"	8.8	179	.0078
1.8	1.8	1.8	"	3.8	"	6.4	130	.0138
2.0	2.0	2.0	"	4.0	"	5.4	110	.0182
2.2	2.2	2.2	"	4.2	"	4.6	94	.0234
2.4	2.4	2.4	"	4.4	"	4.0	82	.0293
2.6	2.6	2.6	"	4.6	"	3.4	69	.0377
2.8	2.8	2.8	"	4.8	"	2.9	59	.0475
DELAYED (1 VOLT) AGC APPLIED TUBE 2 ONLY (CURVE 3)								
<1	0	0	2	2.0	20.4	20.4	416	1/416 EOUT
1.5	.5	.5	"	2.5	"	16.0	326	.0046
2.0	1.0	1.0	"	3.0	"	11.8	241	.0083
2.5	1.5	1.5	"	3.5	"	8.2	167	.0150
2.75	1.75	1.75	"	3.75	"	6.6	135	.0204
3.0	2.0	2.0	"	4.0	"	5.3	108	.0278
3.25	2.25	2.25	"	4.25	"	4.4	90	.0361
3.5	2.5	2.5	"	4.5	"	3.6	73	.0480
AMPLIFIED (X3) AGC APPLIED TUBE 2 ONLY (CURVE 4)								
.2	.2	.6	2	2.6	20.4	15.0	306	.0007
.4	.4	1.2	"	3.2	"	10.2	208	.0019
.6	.6	1.8	"	3.8	"	6.4	130	.0046
.8	.8	2.4	"	4.4	"	3.9	80	.0100
.9	.9	2.7	"	4.7	"	3.1	63	.0143
1.0	1.0	3.0	"	5.0	"	2.5	51	.0196
1.1	1.1	3.3	"	5.3	"	2.0	41	.0268
1.15	1.15	3.45	"	5.45	"	1.7	35	.0329
1.2	1.2	3.6	"	5.6	"	1.5	31	.0387

TABLE I

E_{OUT}	Rectified D.C.	Bias (−) AGC	Bias (−) Initial	Bias (−) Total	Voltage Gain Tube 1	Voltage Gain Tube 2	Voltage Gain Total	e in = E_{OUT}/Gain
DELAYED (1V) AMPLIFIED (X3) AGC APPLIED TUBE 2 ONLY (CURVE 5)								
<1	0	0	2	2.0	20.4	20.4	416	1/416 E_{OUT}
1.3	.3	.9	"	2.9	"	12.6	257	.0051
1.4	.4	1.2	"	3.2	"	10.2	208	.0067
1.5	.5	1.5	"	3.5	"	8.2	167	.0090
1.6	.6	1.8	"	3.8	"	6.4	130	.0123
1.7	.7	2.1	"	4.1	"	5.0	102	.0167
1.8	.8	2.4	"	4.4	"	3.9	80	.0225
1.9	.9	2.7	"	4.7	"	3.1	63	.0301
2.0	1.0	3.0	"	5.0	"	2.5	51	.0392
DELAYED (1V) AMPLIFIED (X5) AGC APPLIED TUBE 2 ONLY (CURVE 6)								
<1	0	0	2	2.0	20.4	20.4	416	1/416 E_{OUT}
1.1	.1	.5	"	2.5	"	16.0	326	.0034
1.2	.2	1.0	"	3.0	"	11.8	241	.0050
1.3	.3	1.5	"	3.5	"	8.2	167	.0078
1.4	.4	2.0	"	4.0	"	5.4	110	.0127
1.5	.5	2.5	"	4.5	"	3.6	73	.0205
1.6	.6	3.0	"	5.0	"	2.5	51	.0314
1.65	.65	3.25	"	5.25	"	2.0	41	.0402
SIMPLE AGC APPLIED TUBES 1 AND 2 (CURVE 7)								
.6	.6	.6	2	2.6	15.0	15.0	225	.0027
.8	.8	.8	"	2.8	13.5	13.5	182	.0044
1.0	1.0	1.0	"	3.0	11.8	11.8	139	.0072
1.2	1.2	1.2	"	3.2	10.2	10.2	104	.0116
1.3	1.3	1.3	"	3.3	9.6	9.6	92	.0141
1.4	1.4	1.4	"	3.4	8.8	8.8	77	.0182
1.5	1.5	1.5	"	3.5	8.2	8.2	67	.0224
1.6	1.6	1.6	"	3.6	7.6	7.6	58	.0276
1.7	1.7	1.7	"	3.7	7.0	7.0	49	.0347
1.8	1.8	1.8	"	3.8	6.4	6.4	41	.0440
DELAYED (1V) AMPLIFIED (X5) AGC APPLIED TUBES 1 AND 2 (CURVE 8)								
<1	0	0	2	2.0	20.4	20.4	416	1/416 E_{OUT}
1.1	.1	.5	"	2.5	16.0	16.0	256	.0043
1.2	.2	1.0	"	3.0	11.8	11.8	139	.0086
1.3	.3	1.5	"	3.5	8.2	8.2	67	.0194
1.35	.35	1.75	"	3.75	6.7	6.7	45	.0300
1.4	.4	2.0	"	4.0	5.4	5.4	29	.0483

TABLE I (CONT'D.)



AGC CHARACTERISTIC CURVES

FIGURE 12

signal required to overload the amplifier.

Curve (3) is for delayed AGC applied to one tube, where the threshold voltage is one volt. Here, maximum receiver gain is utilized until the desired one-volt output is reached. Subsequent control follows a curve of the same nature as (2). However, due to the fact that it has already reached a one-volt value before the curve begins, the delayed AGC curve has better regulation when considered in the ratio sense.

Curve (4) is that of amplified (X3) AGC applied to one tube only. It appears that a more flat characteristic has been obtained by the use of amplification in the AGC circuit. The output has been reduced, and the difference in output for a given variation in input is less than for simple AGC, curve (2). However, the regulation, when considered in terms of db or ratio, is substantially the same as for simple AGC. The same results could be obtained approximately by taking output from a simple AGC circuit through a voltage divider. While it stays closer to the one-volt value, observe how much greater the input must be before the output approaches one volt. We have one advantage over simple AGC here: a much larger signal will be required to overload the amplifier.

Curve (5) is the curve of amplified (X3) AGC with one volt delay applied to one tube. Here we utilize maximum receiver gain until the desired output is reached, and then obtain the type of flat characteristic of (4).

Curve (6) is the same as (5) except that a gain of five is used. The effect of the increased amplification can be compared. In particular, note that for curves (3), (5), and (6), it is only the amount above the one-volt threshold that is reduced, and hence the successive improvement in both change of output voltage and regulation ratio are apparent. This bears out the discussion of delayed amplified AGC in sections 2 and 4 of Chapter II.

Curve (7) is that of simple AGC applied to two tubes. Increased flatness over simple AGC applied to one tube is due to the same cause as for amplified, non-delayed AGC. This demonstrates the inherent amplification obtained by applying AGC to multiple stages as stated in section 4 of Chapter II.

Curve (8) most closely approaches ideal operation. It is the curve of amplified (X5) AGC with one volt delay applied to both stages.

4. Discussion of Assumptions.

It was stated previously that these curves would be in error if initial bias were cathode bias. This error exists because, as the tube is biased down by the AGC voltage, the cathode current decreases, and with it so does cathode bias. If a variable-mu tube were used such that large AGC bias voltages would be employed, variation in cathode bias would be negligibly small by comparison. However, with 6AK5's, when the bias is three volts, the cathode current is about half that for two volt bias, hence cathode bias has dropped from two volts to one volt. So we must have an AGC bias of two volts to give three volts total bias, instead of a one-volt AGC bias as was assumed. For a five volt bias, cathode bias would be negligibly small, so an AGC bias of five volts instead of three would be required to give a five-volt total bias. Knowing the cathode resistor value, we could have determined from the tube characteristic of Ib and Ic_2 vs. control grid volts, values of cathode bias vs. total bias. An auxiliary curve of total bias vs. AGC bias could have been plotted, and these values of total bias could have been used in our calculations.

If the screen were connected through a dropping resistor instead of a voltage divider, it would have been necessary to determine for each total bias the value of screen current and determine from that the screen voltage. Gain would have to be determined from that curve of g_m corresponding to the determined value of screen voltage.

Since it was intended in sections 2 and 3 to show the typical properties of the various AGC types and give a brief explanation of how the curves are determined, the above refinements were left out for the sake of simplicity. They are discussed in this section for completeness of the explanation.

5. Other Graphic Means of Presenting AGC Action.

Another graphical method of determining AGC action has been developed by Amos (1). This method consists of translating the gain vs. grid bias characteristic of the controlled amplifier to a family of curves of input signal level which can be shown on a plot of detector output vs. grid bias. Another independent set of curves, each curve a plot of grid bias vs. detector output for a given type of AGC, are drawn. The intersections of the input voltage curves with one of the AGC curves are the "lock-in" points of that amplifier for that type of AGC.

A curve of input signal level is obtained by taking a given signal level, and, for different values of bias, finding the corresponding receiver gain, and determining the corresponding output voltage. The curve is a plot of output voltage vs. bias for that input.

The AGC curves are simply curves of grid bias vs. detector output for the particular type of AGC. For instance, the curve for simple AGC is: grid bias = detector output. For delayed AGC, delay equal to one volt, it is: grid bias = (detector output - 1), starting with one volt detector output and zero grid bias. For amplified (X5) delayed (1 volt) AGC it is: grid bias = (detector output - 1) X 5, starting with one volt detector output and zero grid bias.

A voltage gain vs. grid bias curve for the two stage amplifier previously discussed in this chapter, with bias applied to both tubes is shown in figure 13. The same assumptions previously made hold for this case. A plot of the type presented by Amos for this amplifier is shown in figure 14. The three types of AGC curves mentioned above appear on this plot. The "lock-in" points for the curve of simple AGC and for amplified (X5) delayed (1 volt) AGC may be compared with curves (7) and (8) respectively of figure 12.

This method of presentation has the advantage that the

2 STAGES 6AK5's

VOLTAGE GAIN vs. GRID BIAS

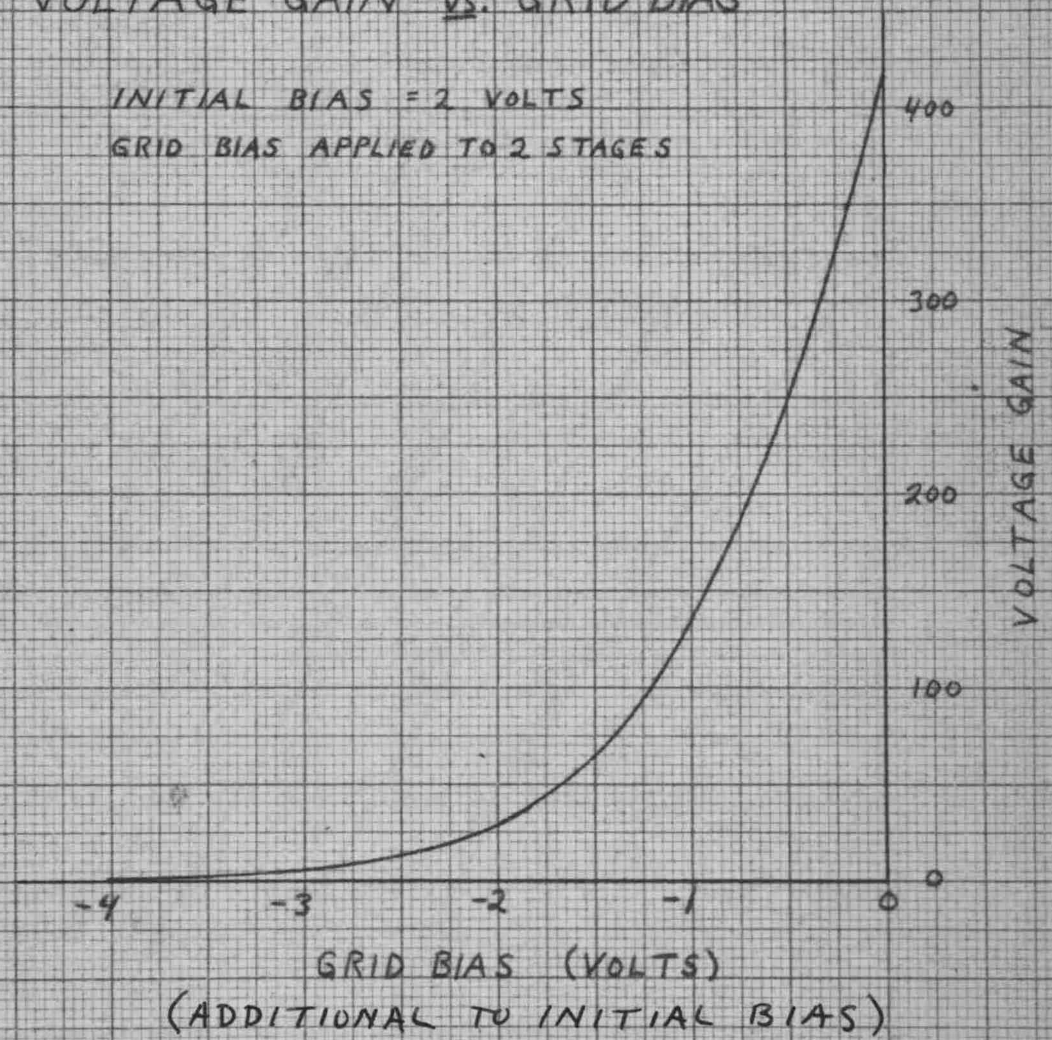
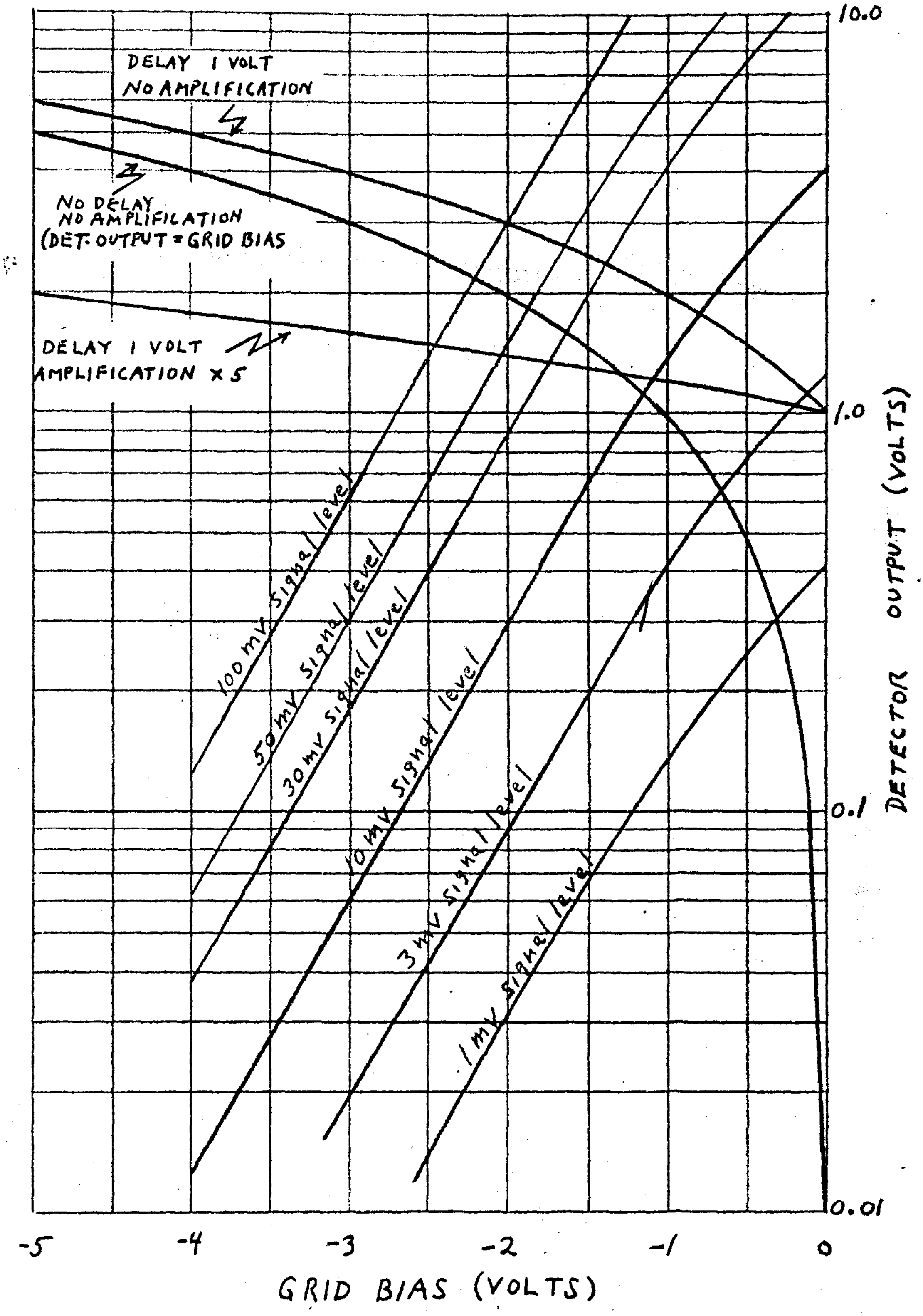


FIGURE 13



AGC CHARACTERISTICS

FIGURE 14

amplifier curves and the AGC curves are independent. AGC curves may be plotted quickly, and for a given amplifier it can be readily determined what type of AGC is necessary to meet the control requirements.

Sturley (8) makes his calculations of the control of an AGC circuit in terms of db ratios. He first constructs g_m vs. bias curves where g_m is in db. He then takes d-c output vs. applied rms carrier of the diode and converts it to a curve of applied carrier in db vs. bias voltage. He then combines these curves by taking a given value of output carrier applied to the diode in db, determining the bias, finding the corresponding g_m (db), and hence determining curve of output carrier (db) vs. input carrier (db). It must be noted that while the results are in terms of db ratios, the reference level for the output carrier is a definite output voltage. This point was brought out in section 4 of Chapter II.

Other helpful curves which may be plotted on the same graph with the AGC characteristic are: (1) Percentage harmonic distortion for a given percentage modulation and modulating frequency (usually 30% at 400 cycles per second) vs. input voltage. (2) The developed AGC bias vs. input voltage. (3) The total bias voltage. If fixed initial bias is used, the last two curves will vary by the amount of the fixed bias. If the initial bias is cathode bias, they will differ by the amount of the initial bias for small inputs, but will run together at high values of input for reasons discussed in section 4 of this chapter.

CHAPTER V

DYNAMIC CONSIDERATIONS

1. General.

So far we have been considering only the static case. We have discussed modulated carriers and AGC filters generally, but in determining the action of the AGC system, we have concerned ourselves only with unmodulated carrier voltages varying at an unspecified slow rate. We have not covered the effect of modulation on the AGC circuit, or just what the filter should filter out, or even decided what constitutes modulation and what constitutes variation of carrier level. in this chapter we shall discuss filters and circuit response to a step variation in carrier amplitude. In Chapter VI we shall look into dynamic response more analytically as a feedback problem.

2. Filters in the Automatic Gain Control Circuit.

One of the main purposes of the AGC system is to remove as nearly as possible the variation in carrier level due to causes such as fading. A desirable quality of a good AGC system is that it will not affect the lower modulation frequencies by "AGC-ing" on them. The choice of values of resistance and capacitance employed in the AGC filter system is a matter of reaching a difficult compromise. The lowest modulation tones are difficult to filter out, and considerable negative feedback may occur at these frequencies, reducing the bass response. A large time constant will filter out these lowest modulation tones, but will slow down the AGC action, reducing its effectiveness against undesired variations. It will be shown in Chapter VI that an appreciable frequency interval exists between the maximum frequency that is satisfactorily suppressed and the minimum frequency that is satisfactorily passed. This is a result of AGC being in effect negative feedback of the low audible and subaudible frequencies, and that sharpness of cutoff is indicative of magnitude of phase shift. Excessive phase shift leads to instability and oscillation, or at least to an enhancement or increase in the magnitude of output of those frequencies in the region of filter cutoff.

It becomes necessary, then, to consider the application of the particular receiver in attempting to decide upon the filter characteristics. For example, in a good quality broadcast receiver, a large time constant might be employed so that audible bass would not be attenuated. Possible rapid variation in carrier level would be accepted as the price. In a short wave communication receiver, where fidelity is not an important factor, but where rapid fading would affect efficient reception of intelligence, a shorter time constant, and hence a more rapidly responding AGC system, would be employed.

It should be noted that there is a difference between the charge and discharge time constants of the AGC filter. When discharging, the diode is non-conducting, and the resistance in the discharge path is the sum of the filter and the diode load resistances. When charging, the diode conducts and effectively short circuits the load resistor.

It is essential that the AGC filter circuit provide an adequate a-c ground for r.f. Furthermore, the AGC filter must insure filtering out of the r-f components. Failure to do so will result in instability and interference whistles. When more than one stage is controlled, separate r-f filters are necessary for each stage to prevent r-f feedback between stages.

A time constant of (Rf X Cf) = 0.1 second is regarded as the most desirable value for the AGC filter under most conditions. However, a high fidelity receiver will require a larger value, possibly as high as 0.5 second. To show the compromises and limitations involved in determining the filter parameters, the following facts are pointed out: To minimize distortion in a back-biased diode delayed AGC system, the ratio of a-c to d-c load resistance must be as near unity as possible, and hence Rf must be as large as possible. However, the total d-c resistance in the grid circuits of the controlled tubes should not exceed the order of magnitude of two megohms. This is because minute traces of gas in a tube result in deposit of positive ions on the control grid. Such deposit results in current in the grid resistor of such polarity as to make the grid less negative. If the grid resistor is too large, the result can become a cumulative decrease in grid bias, increase in space current, increased ion production, greater decrease in grid bias, until the tube may be destroyed by excessive plate current. In addition, the total time constant and total value of Rf are affected by the interstage filters. The effect of these filters can be calculated, and the actual values of Rf and Cf for the AGC filter can be modified accordingly. Also, in an amplified AGC system, where two circuits separated by a tube contribute to a time constant, the overall time constant is approximately the sum of the time constants of the separate circuits.

3. Adjustment Speed of an AGC System.

To determine the system response to a step function change in input level, consider the circuit shown in figure 15. For simplicity, we shall make the following assumptions:

(1) The open circuit rectifier output bears a straight line relation to the i-f output voltage of the amplifier in db. This assumption is justified due to the presence of delay where the output exceeds the delay by an amount that is small compared to the delay. (When $x \ll 1$, $\log(1+x)$ is proportional to x.) This requires that the circuit have a flat AGC characteristic.

(2) The gain reduction in the controlled stages measured in db bears a straight line relation to the d-c AGC bias applied to the grids. This is based on the logarithmic relation between bias voltage and gain in a variable-mu tube.

(3) Only one RC filter section contributes materially to the delay in delivery of control voltage from the rectifier to the grids. This is justified in the case where Rf and Cf are large compared to the filter sections of the individual stages.

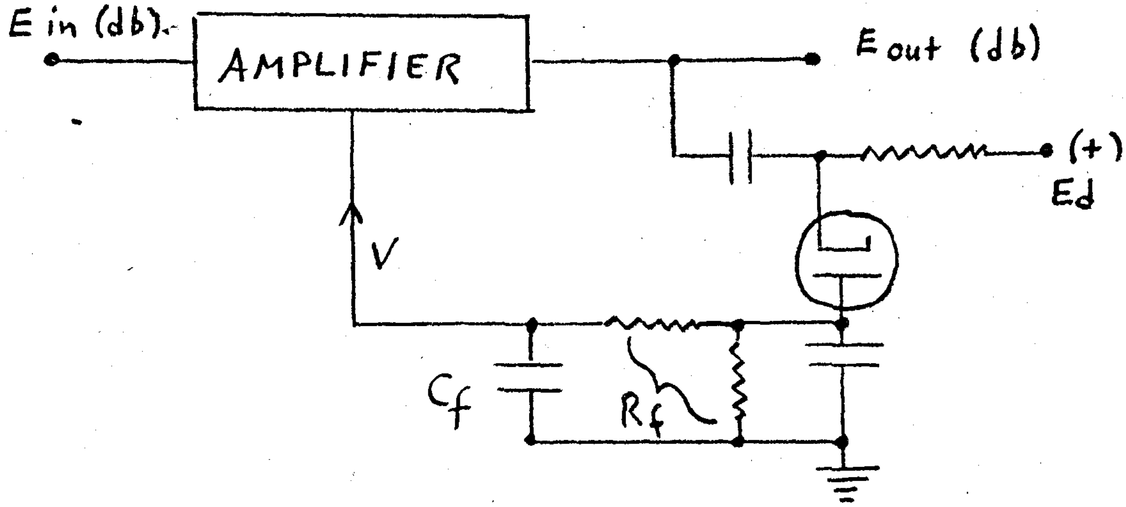
Define: $H = \frac{\text{change in input level (db)}}{\text{change in output level (db)}}$

$k_1 =$ volts increase in d-c rectifier output per db increase in amplifier i-f output.

$k_2 =$ gain reduction of controlled stages in db per volt of AGC bias.

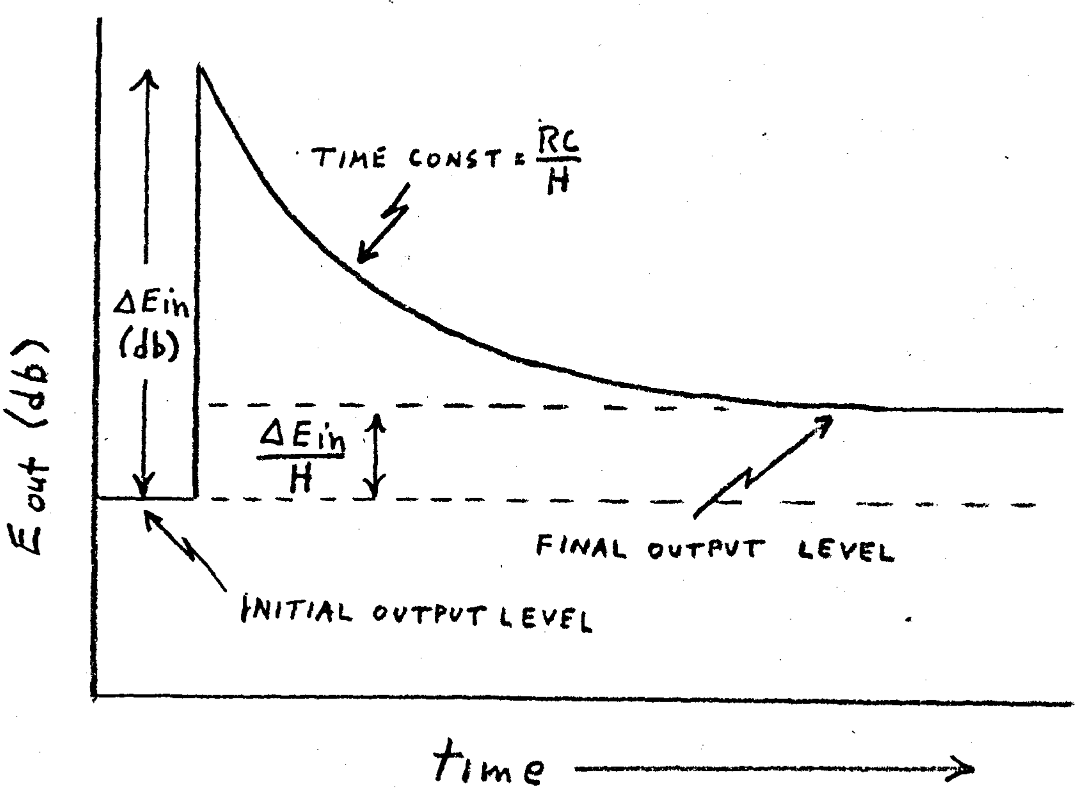
H, then, will be a "flatness factor" of the AGC characteristic; $k_1 k_2 =$ gain reduction of controlled stages in db, per db increase in amplifier i-f output. It can be seen that if $k_1 k_2 = N$, an increase in amplifier output of 1db will cause a gain reduction of Ndb. Hence it will take an $(N+1)$db increase of input to give this one db increase of output. Therefore, $H = (1 + k_1 k_2)$.

It has been shown by Nolle (5) that when the input level is suddenly and permanently increased by a small amount ΔEin(db), the output likewise suddenly increases by the same amount. But with increasing time, the output decreases exponentially and approaches a value which is higher than the original output by ΔEin(db)/H. The time constant associated with this decrease of output to its final value is RfCf/H. This is shown graphically in figure 16.



AMPLIFIER WITH AGC

FIGURE 15



RESPONSE OF AGC SYSTEM TO STEP VOLTAGE

FIGURE 16

CHAPTER VI

FEEDBACK ASPECTS OF AUTOMATIC GAIN CONTROL

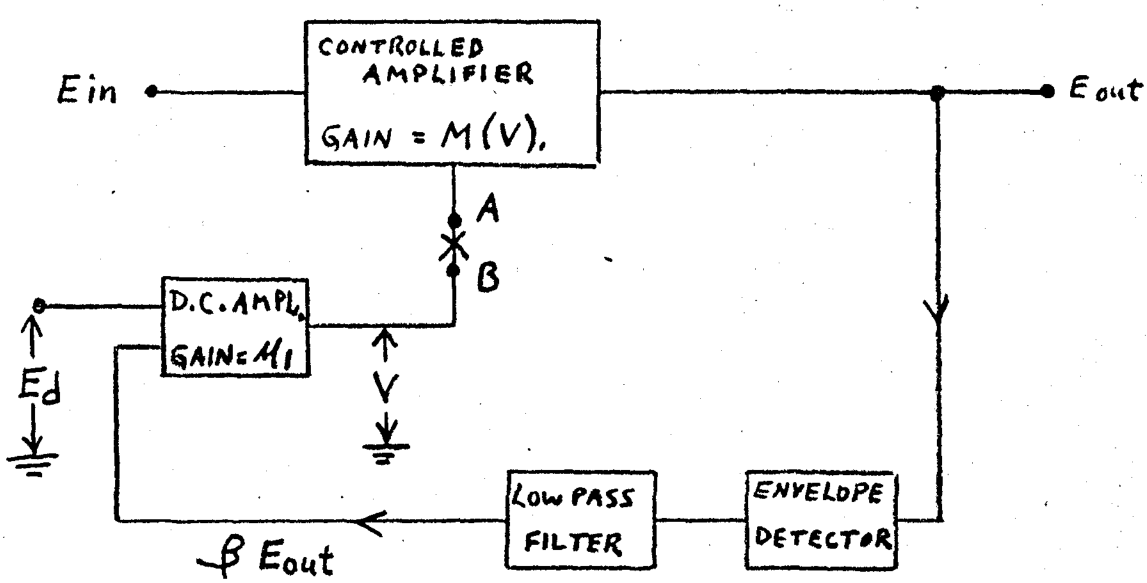
The subject of AGC as a feedback problem has been presented by Oliver (7). A feedback amplifier has an input, an output, a feedback path developing a measure β of the output, a comparison circuit for determining the "net" signal which is the algebraic sum of the input and β, and an amplifier which develops the output from the "net" signal.

Figure 17 shows a block diagram of an r-f amplifier whose gain is proportional to a control potential V, an envelope detector to monitor the output, a low pass filter, and a d-c amplifier which develops the control voltage V proportional to the amount by which the filter output exceeds a threshold voltage Ed. This feedback system is an AGC circuit.

If we replace the threshold voltage by an audio frequency input, and call the variable gain amplifier a modulator, then we have the block diagram of a radio transmitter with envelope feedback. The part of the circuit between the comparison circuit and the output is the "μ" circuit of the feedback amplifier, and the path between output and comparison point is the "β" circuit. For the transmitter, the principle μ-circuit variation might be modulator nonlinearity. In the AGC system it would be fluctuations of input signal strength.

For the transmitter, the feedback equation is:

$$\text{Eout} = \frac{\mu}{1 - \mu\beta}\,\text{Ed}$$



AMPLIFIER WITH AGC AS A FEEDBACK CIRCUIT

FIGURE 17

where μ is the amplification of the " μ "-circuit defined above. If $|\mu\beta| \gg 1$,

$$Eout = \frac{-1}{\beta} \; Ed$$

and the output is independent of μ so that variations in the " μ "-circuit are suppressed. Since, now,

$$\frac{dEout}{Eout} = \left[\frac{1}{1 - \mu\beta}\right] \frac{d\,\mu}{\mu}$$

any variations in the " μ "-circuit are suppressed by the factor: $1/1 - \mu\beta$.

By breaking the circuit at point X and terminating each side in the impedance normally presented by the other side, the loop gain for d.c., $\mu\beta(0)$, when Ein is assumed constant at $\overline{E}$in, is defined as:

$$\mu\beta\,(0) = \lim_{\Delta Va \to 0} \frac{\Delta\, Vb(0)}{\Delta\, Va(0)}$$

where $\Delta\, Va(0)$ is an incremental d-c voltage applied at A, and $\Delta\, Vb(0)$ is the incremental d-c voltage at B caused by $\Delta Va(0)$. The loop gain at frequency ω, $\mu\beta(\omega)$ is:

$$\mu\beta\;(\omega) = \mu\beta(0)Y(\omega).$$

$Y(\omega)$ is the transmission vs. frequency characteristic around the loop normalized to unity at d.c. It is normally the low pass filter characteristic of the " β "-circuit.

If Ein is constant at a value $\overline{E}$in, and V is constant, at $\overline{V}$, the output will be a constant value $\overline{E}$out. M(V) is the envelope gain and

$$\bar{E}out = M(V)\bar{E}in.$$

If, now, V is increased from $\bar{V}$ to $\bar{V} + \Delta\bar{V}a$, then

$$\lim_{\Delta Va \to 0} \frac{\Delta \bar{E}out}{\Delta Va} = \bar{E}in \left[\frac{dM}{dV}\right] \quad V = \bar{V}$$

But $\Delta Vb = \mu_1(0)\, \beta(0)\, \Delta \bar{E}out$, so $\Delta \bar{E}out = \dfrac{\Delta Vb}{\mu_1(0)\, \beta(0)}$.

Hence
$$\mu\beta(0) = \mu_1(0)\beta(0)\bar{E}in \frac{dM}{dV}$$

$$= \mu_1(0)\beta(0)\bar{E}out \left[\frac{1}{M}\frac{dM}{dV}\right].$$

If we let Emin = minimum desired value of $\bar{E}out$

Emax = maximum permissible value of $\bar{E}out$

Vmax = control voltage required to produce maximum required gain reduction in r-f amplifier, then

$$V = \mu_1(0) \left[\beta(0)\bar{E}out - Ed\right]$$

but delay voltage considerations require that for $\bar{E}out$ = Emin, V = 0. Therefore Ed = $\beta(0)$Emin = required threshold. Hence

$$V = \mu_1(0)\beta(0)\left[\bar{E}out - Emin\right].$$

For V = Vmax, $\quad Vmax = \mu_1(0)\beta(0)\left[Emax - Emin\right]$

and hence $\quad \mu_1(0)\beta(0) = \dfrac{Vmax}{Emax - Emin}$

$\mu_1(0)\beta(0)$ is the required amplification of the AGC path. It can be shown from previous equations that

$$\mu\beta(0) = \left[V + \frac{V_{max}}{\frac{E_{max}}{E_{min}} - 1}\right]\frac{1}{M}\frac{dM}{dV}$$

$$\mu\beta(\omega) = \left[V + \frac{V_{max}}{\frac{E_{max}}{E_{min}} - 1}\right]\frac{1}{M}\frac{dM}{dV}\,Y(\omega)$$

It is seen that if $E_{min} = 0$, the condition of no delay, then

$$\mu\beta(\omega) = \frac{V}{M}\frac{dM}{dV}\,Y(\omega)$$

or is independent of the amplification of the AGC circuit, and depends only upon the control characteristic of the r-f amplifier and the control voltage. The output Eout is reduced when the AGC amplification is increased, but the db regulation is not improved thereby. This bears out the discussion in earlier chapters relative to the lack of improvement in the ratio sense with amplified AGC which does not utilize delay.

We have defined M(V) as:

$$\bar{E}_{in} = \frac{\bar{E}_{out}}{M(V)}$$

Differentiating with respect to $\bar{E}_{out}$ and using the relationships already established,

$$\frac{d\overline{E}out}{\overline{E}out} = \frac{1}{1 - \mu\beta(0)} \frac{d\overline{E}in}{\overline{E}in}$$

Thus, an incremental change in the amplitude of the received signal is suppressed in the output by the factor $1/1 - \mu\beta(0)$. This is in accordance with the feedback theory since μ has been shown to be proportional to $\overline{E}in$ in the feedback circuit.

If the input modulation is an incremental voltage $\Delta \overline{E}in(\omega)$, similar analysis shows that $m_2(\omega) = \frac{Ya(\omega)}{1 - \mu\beta(\omega)} m_1(\omega)$.

where $m_1 = \Delta\overline{E}in(\omega)/\overline{E}in$, the input modulation index

$m_2 = \Delta\overline{E}out(\omega)/\overline{E}out$, the output modulation index

$Ya(\omega)$ = the modulation vs. frequency characteristic of the r-f amplifier.

Letting $Ym(\omega) = m_2/m_1$, the modulation vs. frequency characteristic with AGC, then

$$Ym(\omega) = Ya(\omega)/1 - \mu\beta(\omega).$$

These equations hold in linear form provided input modulation index is small or frequency so ~~small~~ high that only a small variation in the amplifier gain occurs during the cycle. Otherwise harmonic distortion of the received r.f. is produced.

$Ya(\omega)$ is the selectivity characteristic of the r-f amplifier centered about d.c. rather than the carrier frequency and normalized to unity.

Without AGC, the modulation transmission characteristic is that of a simple low pass filter having a flat transmission in the low frequency region. With AGC the situation is different. At high frequencies $\mu\beta \ll 1$ and $Ym(\omega) \approx Ya(\omega)$ so that high frequency modulation is unaffected by the AGC. At d.c. and very low frequencies, $\mu\beta \gg 1$ and $Ym(\omega) \ll Ya(\omega)$. The transmission of low frequency modulation is therefore reduced by AGC and a low frequency cutoff is introduced.

This cutoff (where $Ym(\omega)$ is down 3db) will be at about the frequency of loop gain crossover (where $|\mu\beta| = 1$). This results from the fact that if $\mu\beta(0)$ is high, then when $|\mu\beta| = 1$, β is close to 90° phase angle. This amplifier cutoff is at a much higher frequency than the cutoff frequency of the low pass filter. This is because the cutoff frequency of the low pass filter occurs when $|\mu\beta|$ is down 3db, as compared to the many db attenuation for amplifier cutoff.

It is thus seen that there is a frequency interval in which modulation is only partly transmitted and the frequencies of carrier variation are only partly suppressed. By using a sharper low pass filter, we can extend the low frequency modulation transmission down lower for the same AGC frequency response, or, maintaining the same lower limit of modulation transmission, provide faster AGC action by raising the cutoff frequency of the low pass filter. In other words, the sharper the filter cutoff, the more closely the gain crossover frequency approaches the filter cutoff frequency, and a smaller frequency interval is utilized to drop the AGC loop gain. However, stability requirements and the permissible low frequency gain enhancement limit the sharpness of cutoff that can be used.

The modulation vs. frequency characteristic with AGC has been given as:

$$Ym(\omega) = \frac{Ya(\omega)}{1 - \mu\beta(\omega)}.$$

For the system to be stable, all roots of the equation $1 - \mu\beta = 0$ must have negative real parts. Nyquist (6) has shown that if a polar plot is made of the magnitude and phase of $\mu\beta$ as a function of frequency and the curve does not enclose the point, $1 \underline{/0}$, then $1 - \mu\beta = 0$ has no roots with positive real parts, and the system is stable. This is known as Nyquist's criterion and such a plot is called a Nyquist diagram. For negative feedback, the phase at zero frequency is 180^{o}. The phase change of the low pass filter $Y(\omega)$ with frequency reduces this value. If the phase reaches zero degrees, and the loop gain $|\mu\beta|$ is greater than unity, oscillations will occur.

Bode (2) has shown that there is a definite relation between transmission characteristic and phase shift. Thus, if the amplitude of transmission is specified as a function of frequency, then the phase shift characteristic with frequency is determined, and vice versa. The phase shift depends upon the <u>variation</u> in amplitude of transmission with frequency. There is an irreducible minimum amount of phase shift associated with a given amplitude vs. frequency characteristic. If the transmission is constant with frequency, the phase shift will be zero. If the amplitude of transmission varies at a constant slope expressed in db per octave, the phase shift is constant and is $\pi/12$ times this slope. If the slope is not constant, the phase shift at a given frequency is $\pi/12$ times the slope at that frequency, modified somewhat by the weighted slope at adjacent frequencies. A constant slope of 6db per octave will indicate 90° phase shift, and a slope of 12db per octave will indicate 180° phase shift. If slope is fairly constant, such values will hold approximately.

To avoid oscillation in a feedback circuit, then, instead of saying that phase shift must not reach 180° until $|\mu\beta|$ is well below unity, we can say that it is necessary that $|\mu\beta|$ not vary to rapidly with frequency until it is well below unity. In fact, to design a feedback system to avoid oscillation, one need consider only the way in which the amplitude of transmission varies with frequency. In general, to keep the phase shift appreciably less than 180°, the rate at which $|\mu\beta|$ may be reduced is limited to about 9db per octave. The problem of shaping the cutoff characteristic of a feedback system is treated extensively by Bode.

The system would be stable if the Nyquist criterion were met. If, however, $|\mu\beta|$ was reduced to unity at a phase angle slightly greater than zero, then $1 - \mu\beta$ would be small, and serious enhancement of modulation frequencies would occur. In order not to increase the modulation transmission at any frequency, $|1 - \mu\beta|$ must be greater than or equal to unity at all frequencies. This would require that, on a Nyquist diagram, $\mu\beta$ stay outside a unit circle drawn about the point 1 $\underline{/0}$. In practical cases, it is desirable that the phase margin (the phase angle at which $|\mu\beta|$ is reduced to unity) be of the order of 50° or so. At high frequencies (with respect to the filter), as $|\mu\beta|$ approaches zero, the maximum allowed phase shift angle to still remain outside the above-mentioned unit circle, becomes limited to 90°. Thus, for zero gain enhancement, the loop gain must not fall faster than 6db per octave at the high frequencies.

From the above discussion it can be seen that the sharpness of filter cutoff is limited. This requires a definite frequency interval between the frequency band satisfactorily passed (the intelligence) and the frequency band satisfactorily suppressed (the undesired carrier variations). In general, the greater the loop gain, the larger will be this frequency interval due to the limit on the rate of reduction of transmission with frequency. This is the basic reason for the necessity of compromise in deciding upon the filter time constant. It is not a matter of drawing a line between the desired and undesired frequencies, but rather one of sliding a band up and down the spectrum, the ends of which band determine the upper limit of the undesired and the lower limit of the desired frequencies. When it is considered that this band is a matter of octaves in extent, it is easy to understand that by sliding it one way to uncover a frequency at one end, we must coverup a frequency at the other end, and vice versa. Thus, for example, to speed up the AGC to suppress two cycle variation instead of one cycle, we might have to attenuate frequencies below 50 cycles instead of below 25 cycles per second.

Since $Ym(\omega)$ is a complex admittance characteristic, it can be used to determine the transient response A(t) of the system to an incremental step in received signal amplitude. Since the amplifier bandwidth is usually large compared with that of the AGC system, $Ya(\omega)$ can be considered as unity.

Since we can assume $\mu\beta(\infty) = 0$, there can be no instantaneous response, and hence $A(0) = 1/1 - 0 = 1$. The ultimate output $A(\infty)$, will be $1/1 - \mu\beta(0)$. Thus a step function of one percent applied to the input would produce an initial one percent increase in output amplitude, but this would ultimately decrease to $1/1 - \mu\beta(0)$ percent. The form of the intervening transient will be determined by $\mu\beta(\omega)$. Thus the response as determined by feedback theory is in accord with the results shown in section 3 of Chapter V, with k_1k_2 corresponding to $-\mu\beta(0)$.

CHAPTER VII

CONCLUSION

1. The Place of AGC in Receiver Circuitry.

Automatic gain control is an important auxiliary circuit in a receiver. Its general adoption is indicated by the fact that practically all receivers, regardless of cost, have some form of AGC. To obtain the most satisfactory results in the AGC system, the same quality of engineering must be employed in this circuit as is employed in the design of the receiver proper. Several problems of the receiver design are intimately tied in with the design of the AGC circuit: expected range of input signal strengths, minimum usable input signal, permissible variation of output, expected maximum frequency of variation of input signal strength, minimum frequency which must be passed without attenuation, permissible distortion, number and type of tubes to be used in stages subject to control, availability of a negative d-c voltage source, et cetera.

The selection of the AGC system is a two-way compromise. The first is AGC performance vs. cost and complexity. The second is AGC performance vs. the sacrifice of some desirable receiver features. As for the first compromise, the desired performance can be obtained in many cases with an inexpensive, non-complex circuit such as simple AGC. If, however, a receiver is to handle very small signals, and yet be able to provide a fairly flat characteristic for a large range of inputs, then, either an extra tube, a source of negative supply voltage, or both, is required. The second compromise is more stubborn. Careful consideration must be given to differential distortion, distortion due to exceeding the signal handling capacity of the last i-f stage, and distortion involved in compensated AGC in the audio stage. These may result in attempting to obtain high AGC performance, and may have to be accepted to some degree. The low frequency response problem must be met on a give-and-take basis, sacrificing speed of the AGC system for low frequency response or vice versa.

2. Miscellaneous Automatic Gain Control Circuits.

Certain other types of circuits sometimes come under the heading of AGC circuits. These are: the quieting or squelch circuit which cuts off the audio output when no carrier is present; the volume expander which increases gain for large signals and decreases it for small signals, providing greater contrast in volume range; and the volume compressor which does the reverse of the expander by decreasing gain for large signals and increasing it for small signals. All of these circuits normally perform at audio frequencies.

There are certain special circuits which demand that AGC be not employed. The loop radio detection finder is an example of such a circuit. If AGC were used, the sharpness of the null would be greatly reduced, since the receiver would be operating at maximum gain when trained on the null, and would be working at less sensitivity when trained to one side of the null.

3. Trends of the Future.

Automatic gain control promises to be a most important circuit type in future developments. The particular field is that of high speed unmanned vehicles. Here, the large and rapid variations in signal strength at the antenna, as the vehicle approaches or recedes from the signal source, require that the AGC circuit take over the task normally vested in a manual r-f gain control. In some applications it is essential that control be performed within very small tolerances, such that the output be maintained above a threshold value with possible variation not exceeding a few db. AGC techniques must be applied to pulsed systems, and will be required to suppress much higher frequency variations in input signal strength than in conventional receiver design.

Thus, automatic gain control circuits of much higher gain and much higher response speeds, which will require more circuitry, more tubes, and new design techniques, have become the latest field of development for this subject.

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